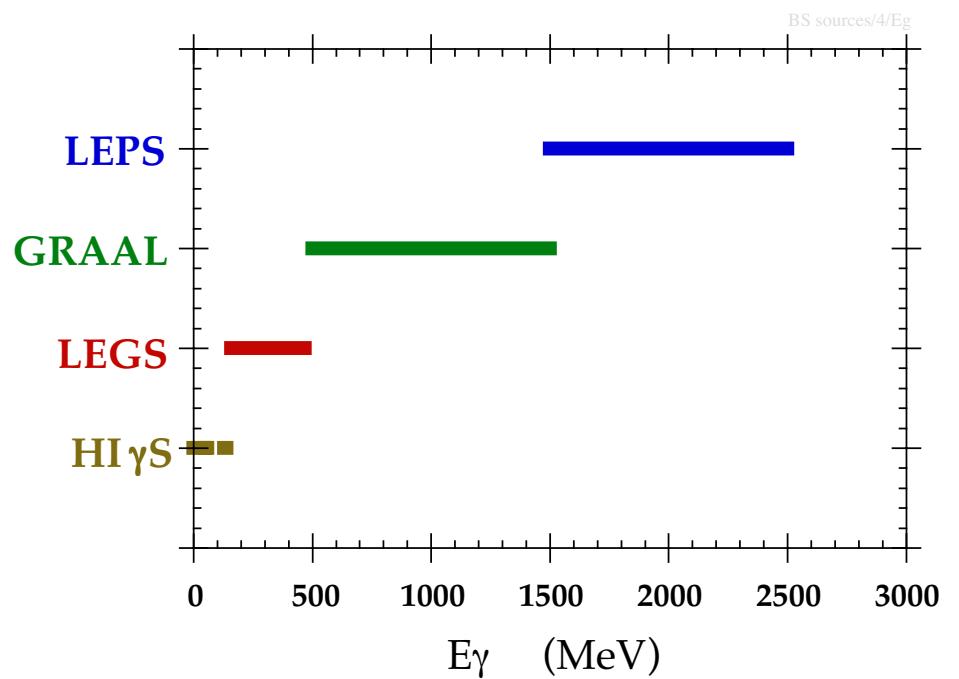


“Low Energy Photon Beam Experiments at SPRING-8, BNL-LEGS, HIGS, GRAAL”

A.M. Sandorfi, Brookhaven National Lab

- **Laser-Electron-Photon-Source (LEPS)** on the 8 GeV SPring-8 ring in Harima Science Garden City, Japan.
- **GRenoble-Anneau-Accélérature-Laser (GRAAL)** facility on the 6 GeV ESRF ring at Grenoble, France
- **Laser-Electron-Gamma-Source (LEGS)** on the 2.8 GeV NSLS ring at Brookhaven National Lab, NY, USA
- **High-Intensity Gamma Source (HI γ S)** on the 1.2 GeV Duke Free Electron Laser ring, Durham, NC, USA,



chief chefs for today's menu:

T. Nakano, J.-K. Ahn
S. Daté

*Laser-Electron-Photon-Source
(LEPS)*

C. Schaerf, A. D'Angelo

*GRenoble-Anneau-Accélération-Laser
(GRAAL)*

AMS

*Laser-Electron-Gamma-Source
(LEGS)*

H. Weller, B. Norum
V. Litvinenko

*High-Intensity Gamma Source
(HI γ S)*

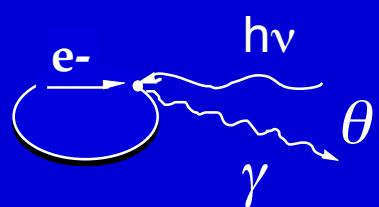
*Backscattered Photon Workshop, June 27–29, 2002
Monteporzio Catone, Italy*

Polarized γ beams from laser- e^- backscattering

$$E_\gamma = \frac{4\epsilon_\ell(E_e/m_e)^2}{1 + 4\epsilon_\ell E_e/m_e^2 + \vartheta^2(E_e/m_e)^2}$$

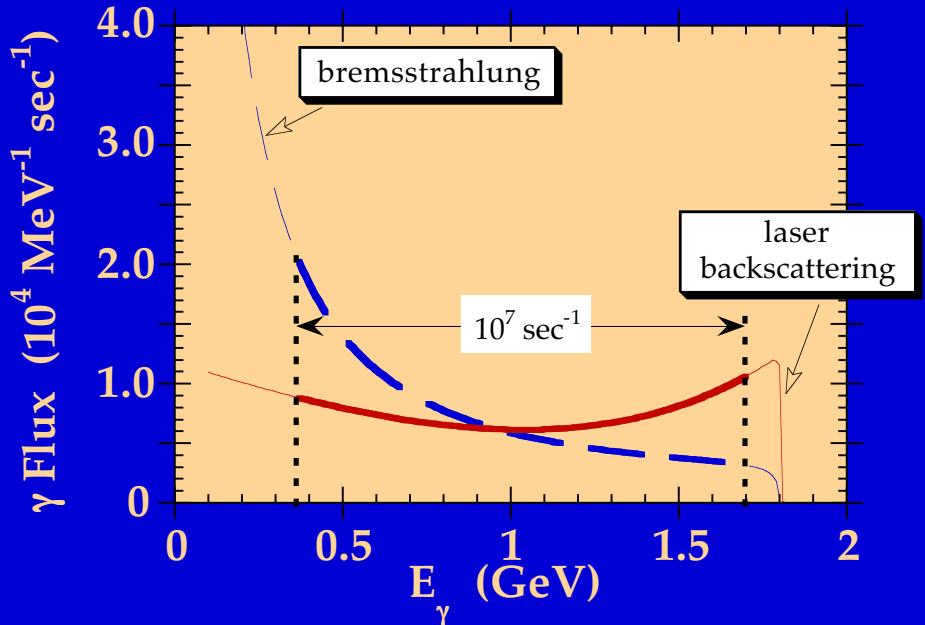
5 eV $(5000)^2$

500 MeV

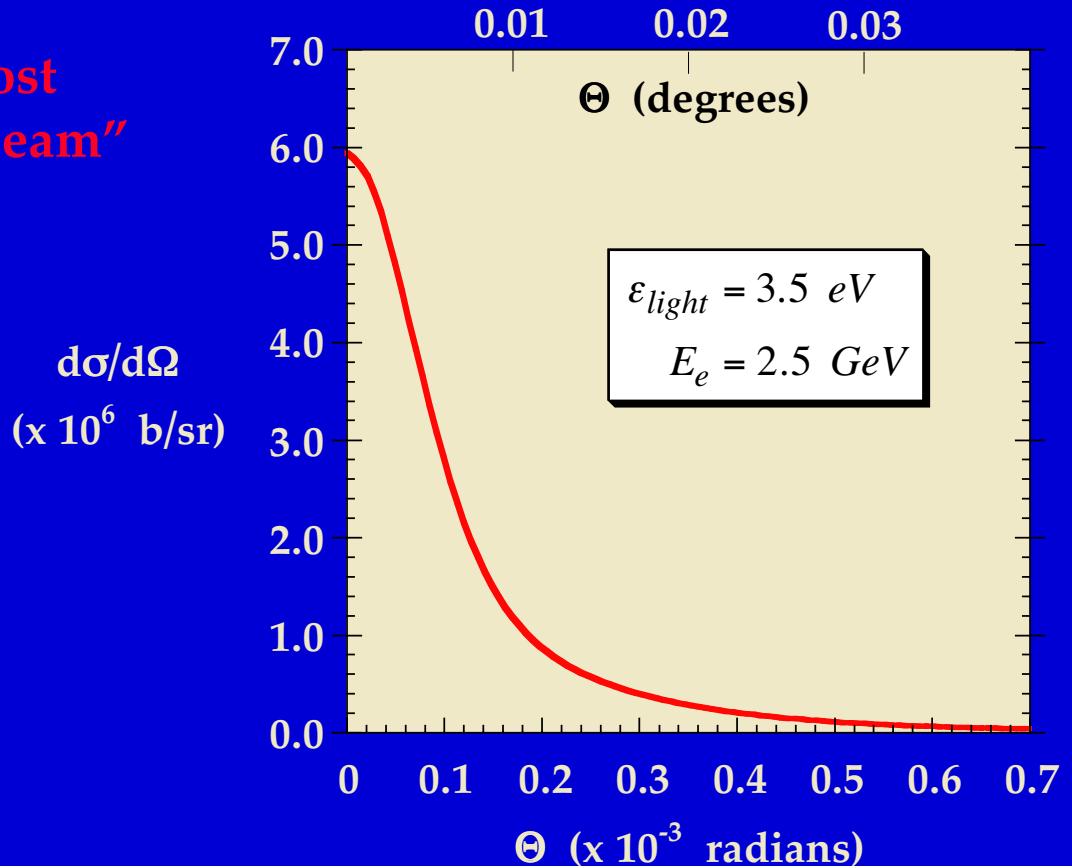


ΔE_γ definition :

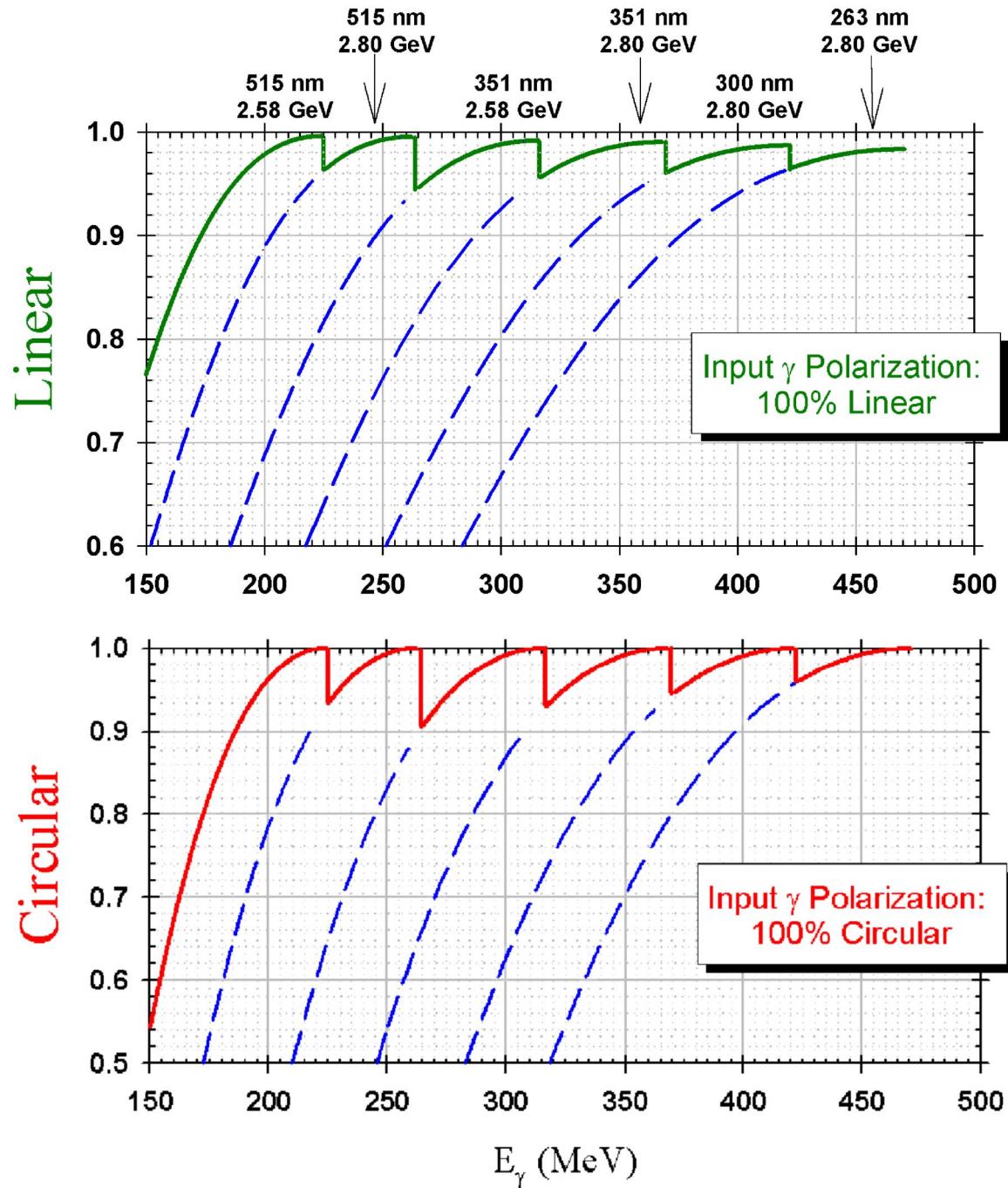
- collimation
- e' tagging



Lorentz Boost creates a "beam"



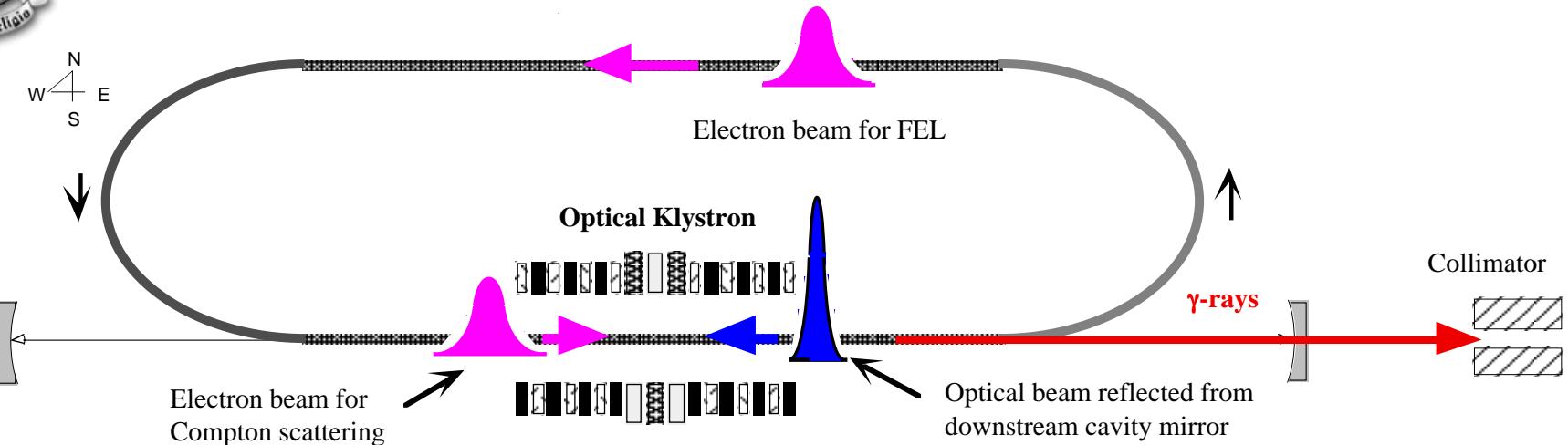
LEGS Beam Degree of Polarization



<i>Facility :</i>	<i>HIGS</i>	<i>LEGS</i>	<i>GRAAL</i>	<i>LEPS</i>
Location	Durham	BNL	Grenoble	Harima
Storage ring	DFELL	NSLS	ESRF	SPring-8
Electron energy (GeV) :	1.0	2.8	6.0	8.0
Electron current (mA) :	25 (\rightarrow 200)	250	200	100
Photon energy (eV) :	0.6 - 6.2 (\rightarrow 12)	2.4 - 4.7	3.5	3.5
Gamma-ray energy (MeV) :	0.6 – 58 (\rightarrow 200) variable	150-470 simultaneous	550-1470 simultaneous	1500-2400 simultaneous
Energy defining method :	collimation	external tagging	internal tagging	internal tagging
Energy resolution (%) :	0.5 – 1.0	0.6	1.1	1.25
FWHM (ΔE MeV) :	0.005 – 1.0	3	16	30
Beam rate on target (s^{-1}) :	$7 \cdot 10^6$ ($\rightarrow 10^8$)	$4 \cdot 10^6$	$2 \cdot 10^6$	$2 \cdot 10^6$
Beam intensity ($s^{-1} \Delta E^{-1}$) :	$4 \cdot 10^7$ ($\rightarrow 10^8$)	$1 \cdot 10^5$	$3 \cdot 6 \cdot 10^4$	$6 \cdot 10^4$

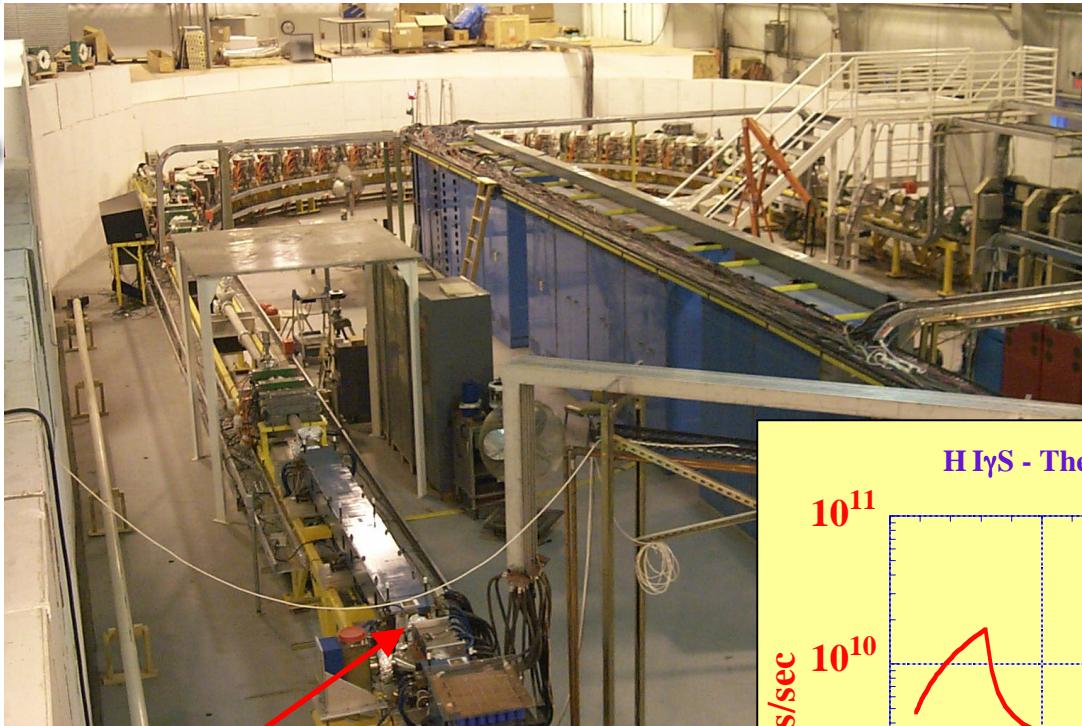


HI γ S at the OK-4/Duke Storage ring FEL



Advantages of Storage Ring FEL based HI γ S

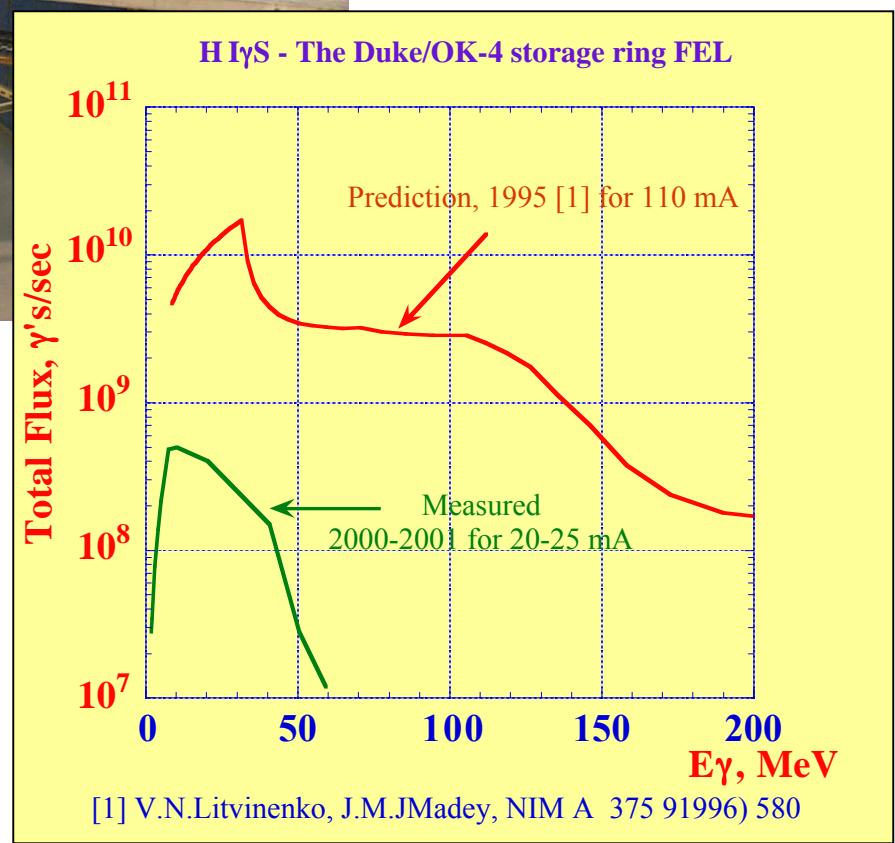
- FEL operation: guarantees alignment for γ -ray production
- γ -ray energy defined by collimation, rather than e-tagging
- High intra-cavity power enhances the γ -ray flux
- Tunability of FEL makes γ -ray beam energy tunable
- Low emittance (<10 nm rad) \Rightarrow narrow γ -rays energy spread



Collision point

- typical resolution $\sim 0.5\text{-}1.0\%$ of $E\gamma$;
- $\sim 1.5\%$ of the total flux for each 1% FWHM of the γ -ray energy spread;
- Polarization $\sim 100\%$ (lin/cir)

Energy of γ -ray beam
is continuously tunable
from 0.6 to 58 MeV





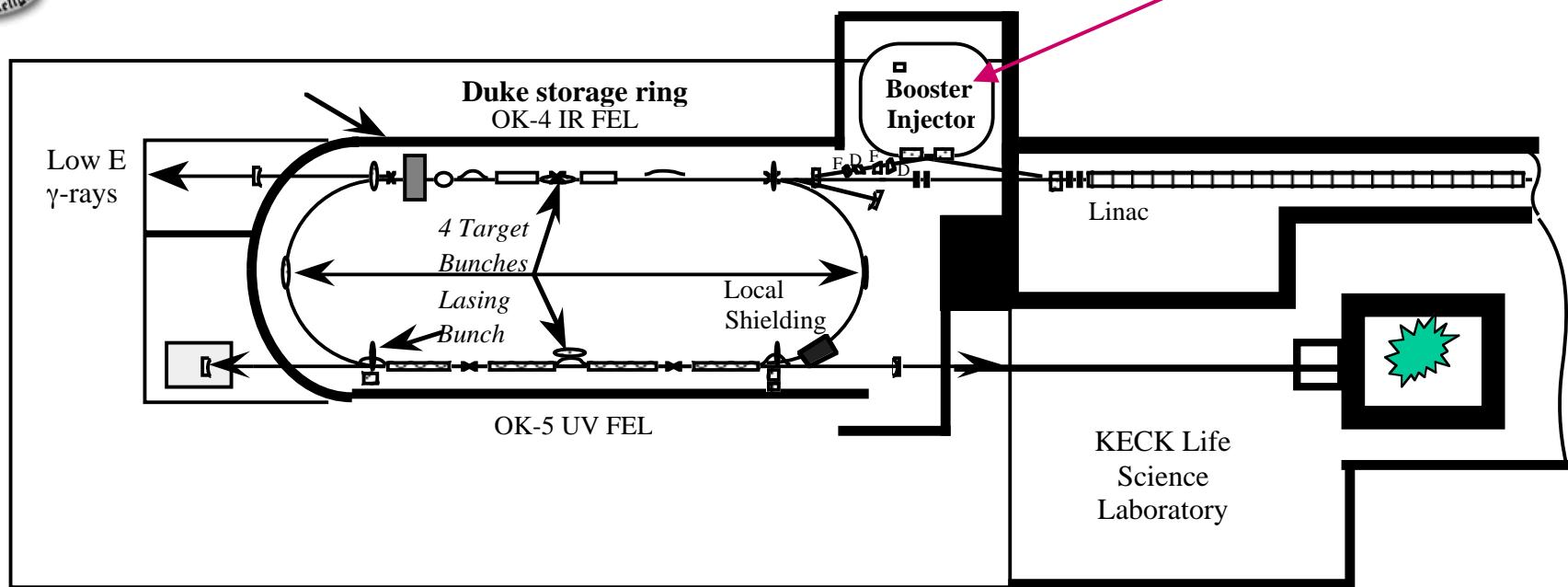
Modes of SR FEL HI γ S

- “No-loss” mode
 - γ -rays energy is less than energy acceptance of the ring (~ 20 MeV @ Duke)
 - Max γ -ray flux is limited by energy spread growth in the e-beam ($\sim 5 \cdot 10^{13} \gamma'$ /sec, 200 mA, 1 GeV @ Duke)
- Loss mode
 - energy of γ -rays exceeds the acceptance of the ring
 - Max γ -ray flux is limited by the top-off injector capabilities ($\sim 10^{11} \gamma'$ /sec, with future full energy booster-injector @ Duke)
 - or by the ramping speed ($\sim 10^6 \gamma'$ /sec @ Duke)



Future HI γ S

Commissioning - 2004



γ -rays energy range: **from 2 MeV to 200 MeV**

Polarization: **Circular (left or right), Linear x/y**

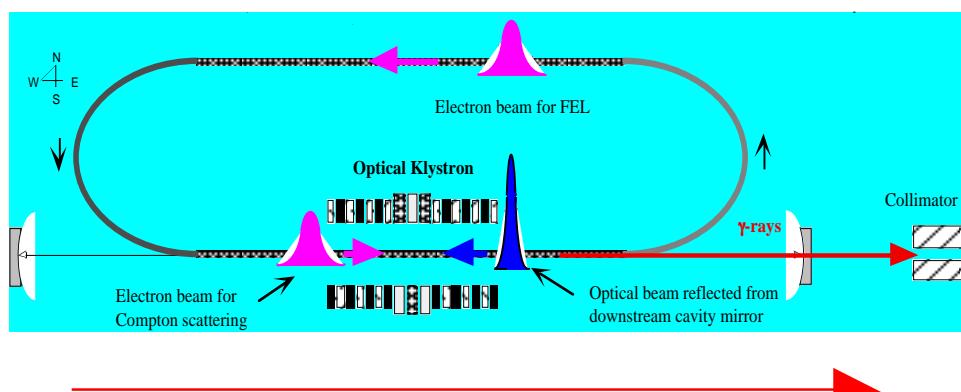
γ -rays energy resolution: **from 0.4% to 1%**

Total γ -ray flux: **from $5 \cdot 10^8$ to 10^{11} per second**



The spectrum of HI γ S activities:

H
I
 γ
S



h i g s

Collaborations

Σ gerasimov-drell-hearn

Π nuclear resonance fluorescence

α nuclear astrophysics

γ Nuclear Spectroscopy / Applications

p compton scattering

n few-body studies

π photo-pion production

PAC & other info

Measurements of I_d^{GDH}

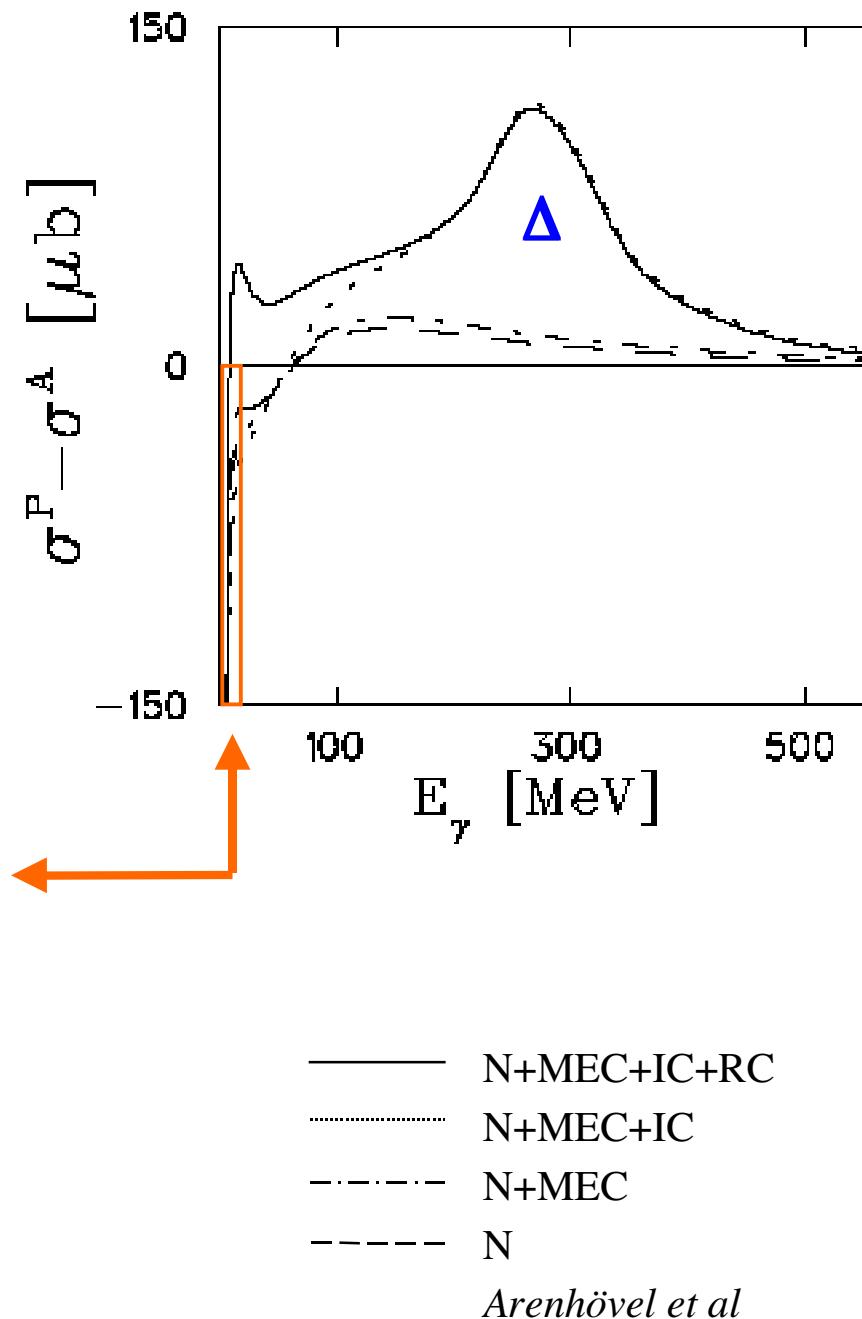
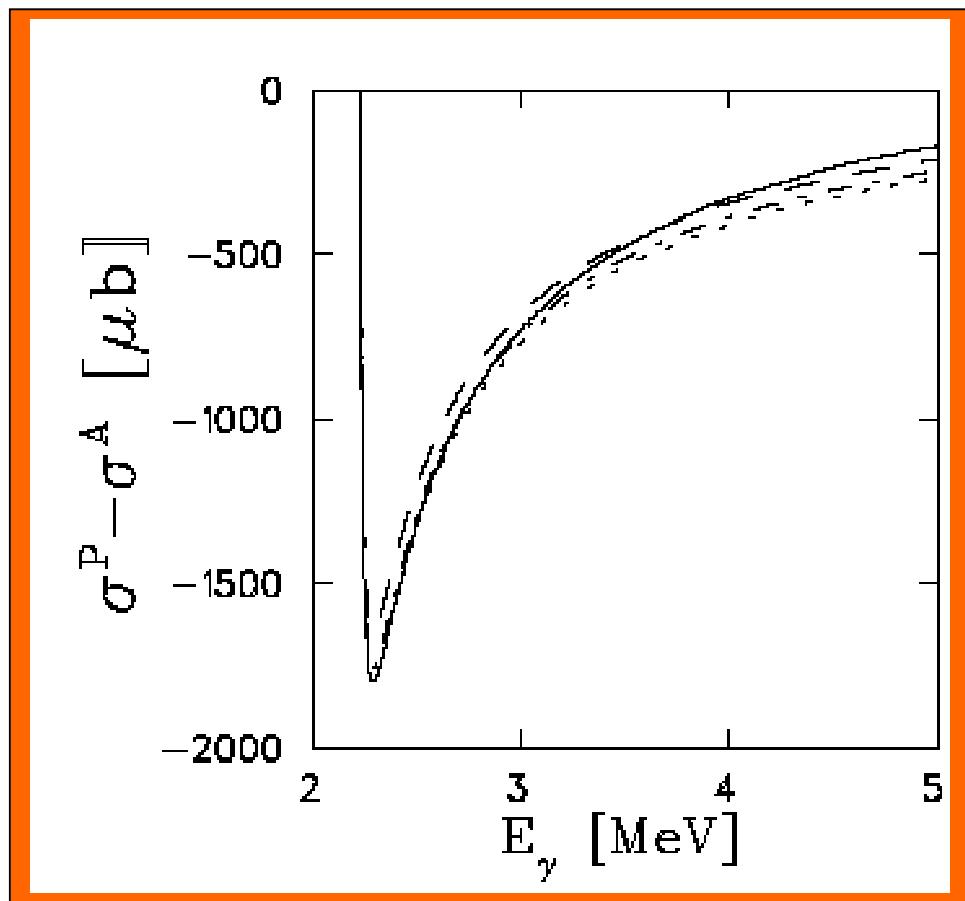
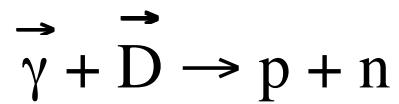
Derivation of GDH Σum Rule did not require target to be nucleon

$$I^{GDH} = \frac{4\pi^2\alpha}{m^2} \kappa^2 S = \int_{\omega_0}^{\infty} \frac{\sigma_+ - \sigma_-}{\omega} d\omega$$
$$= \begin{cases} 205\mu b \text{ for } p (\kappa_p = +1.79) \\ 233\mu b \text{ for } n (\kappa_n = -1.91) \\ 0.6\mu b \text{ for } d (\kappa_d = -0.14) \end{cases}$$

Interesting to measure as test of assumptions for composite system

Note: ω_0 for nucleon case is pion production threshold, about 150 MeV

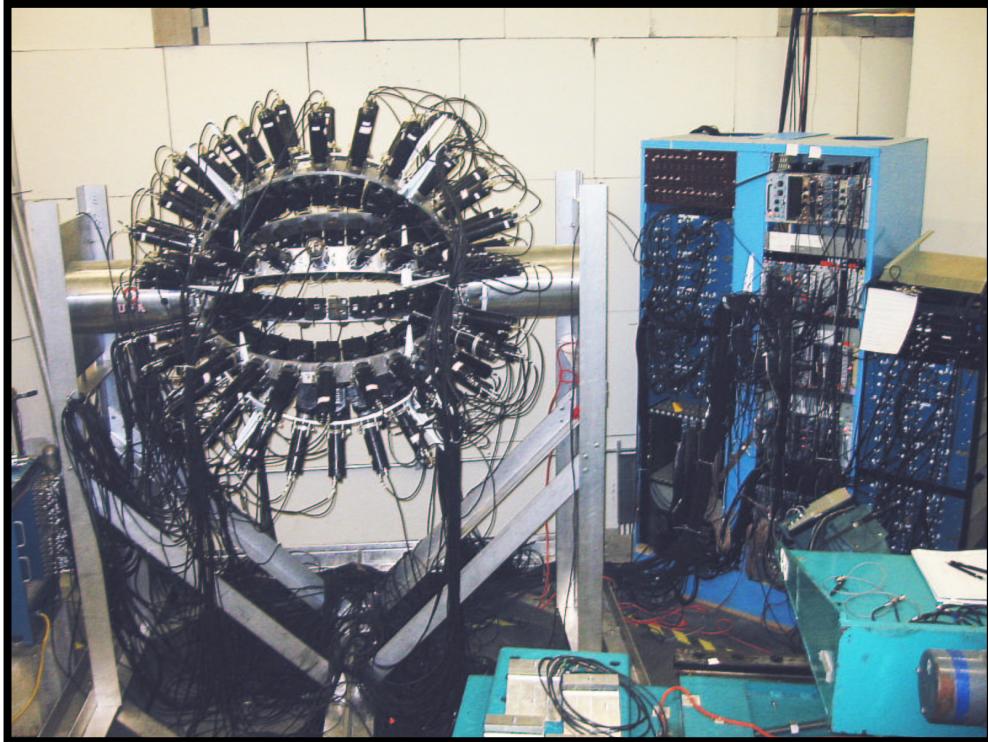
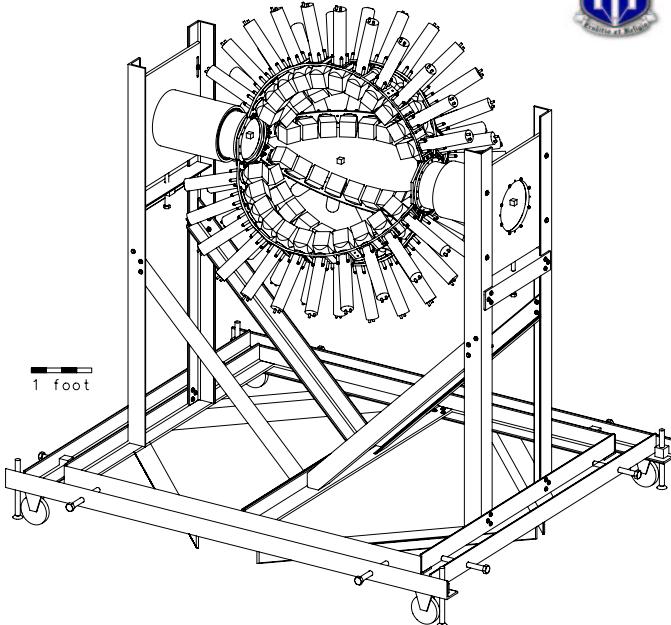
ω_0 for deuteron case is breakup threshold, about 2.24 MeV!



The BLOWFISH Segmented Neutron Detector



- 88 BC-505 cells
- 11 Bites in ϕ
- 8 Bites in θ
- 1/4 4π coverage



Low energy $\vec{\gamma} \vec{D} \rightarrow p n$, pre-polarized target:

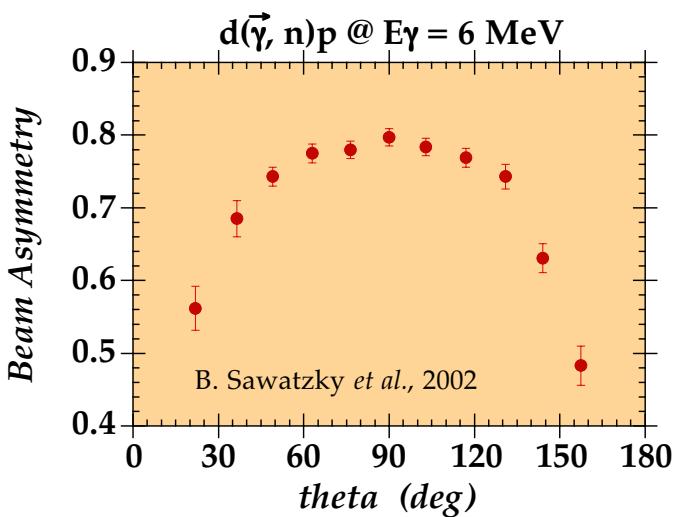
- dominated by S and P wave components ($^{2S+1}L_J$)

$$\frac{\pi}{2k^2} \left\{ \begin{array}{c} {}^1S_0 {}^2 \\ \end{array} \right\} \cong 3 \cdot \sigma(M1)$$

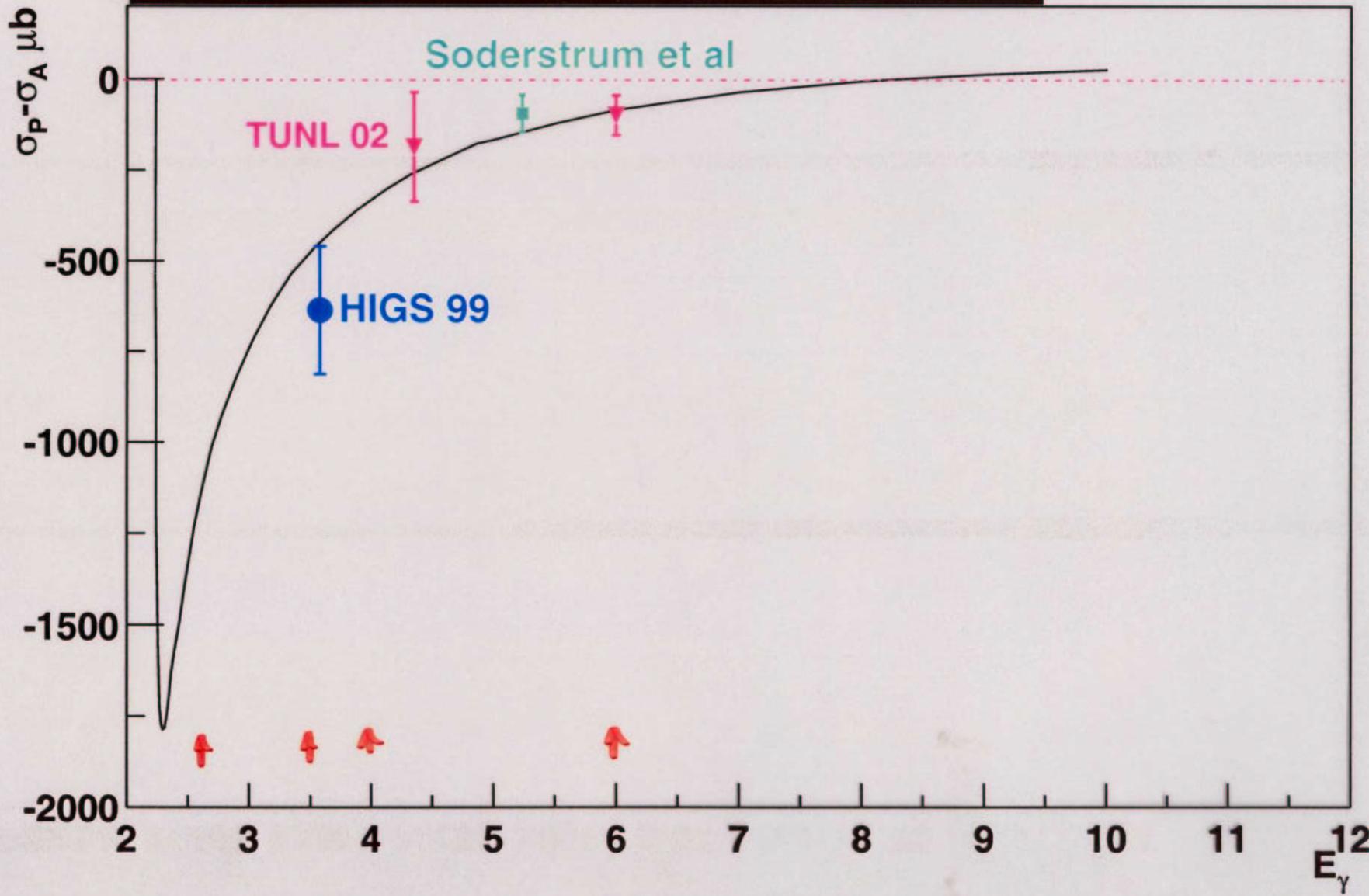
↑ ≈ 0
↓ ≈ 0

- $$\sigma_P - \sigma_A \approx \frac{\pi}{2k^2} \left\{ \begin{array}{c} - \boxed{{}^1S_0 {}^2} - \frac{3}{2} \cdot {}^3S_1 {}^2 \\ - \boxed{{}^3P_0 {}^2 - \frac{3}{2} \cdot {}^3P_1 {}^2 + \frac{5}{2} \cdot {}^3P_2 {}^2} \end{array} \right\}$$
- $\Rightarrow \sigma_P - \sigma_A \approx -3 \cdot \sigma(M1)$

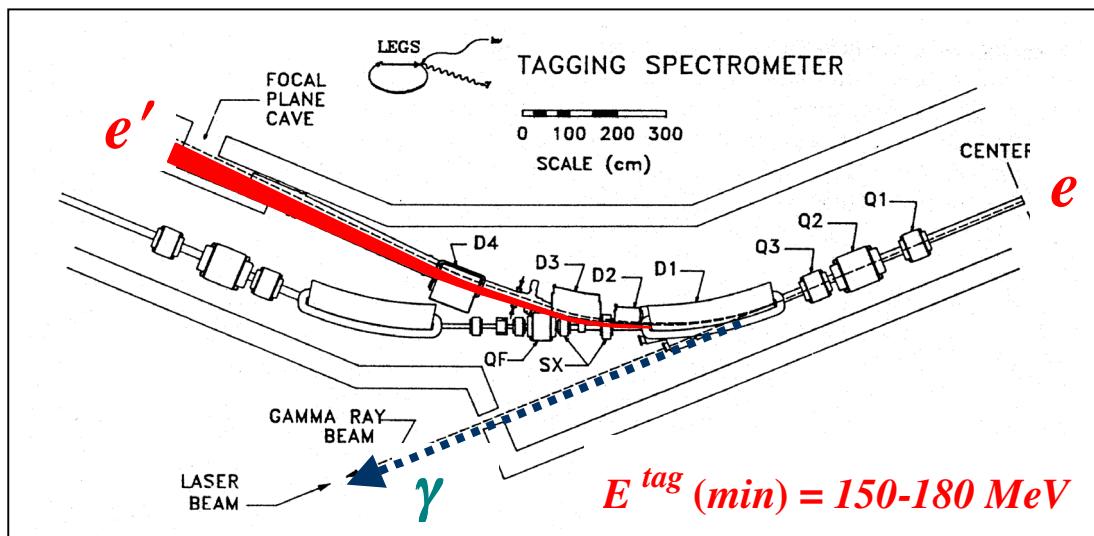
- separate M1 from E1 using **Beam Asymmetry** with linear polarization



$\sigma_P - \sigma_A$ prediction and indirect results



Laser-Electron-Gamma-Source (LEGS)

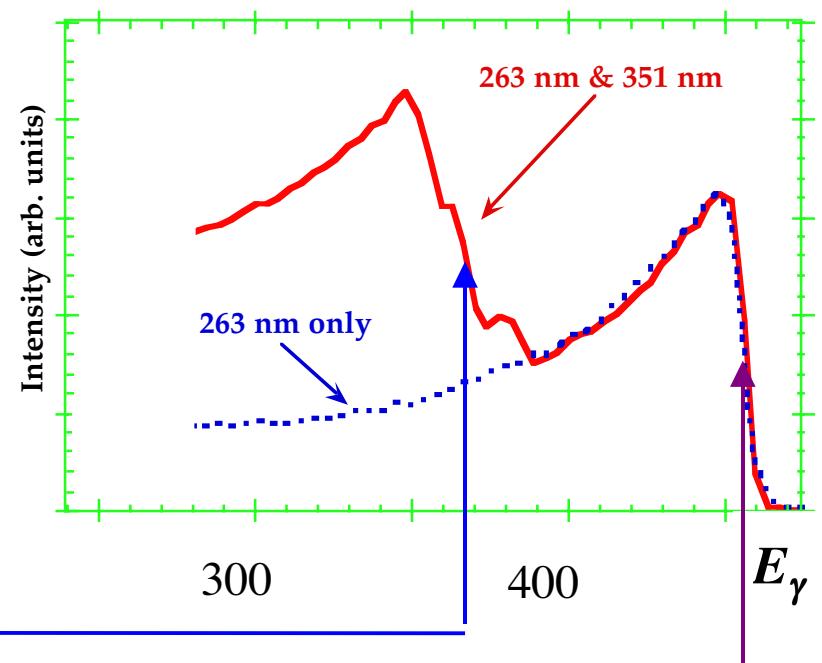


$$\text{NSLS } E_e = 2.8 \text{ GeV}$$

γ beam energy determined by e' tagging

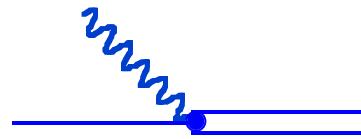
$$E_\gamma = E_e - E_{e'}, \quad \Delta E_\gamma = 3 \text{ MeV}$$

4ω Nd-YLF ring laser		Ar-Ion laser			
$\lambda(\text{nm})$	263	300	351	488	515
E_γ (max)	471	421	368	275	262
	MeV	MeV	MeV	MeV	MeV



LEGS p($\vec{\gamma}$, π) and p($\vec{\gamma}$, γ) experiments – PRC64, 25203(2001)

$p \rightarrow \Delta^+$ transition :



$$\text{EMR} = -3.07 \pm 0.26 \pm 0.24 \ (\%)$$

$$G_{E2} = + [0.137 \pm 0.012 \pm 0.043]$$

$$A_{I/2} = -135.74 \pm 1.34 \pm 3.71 \ (10^{-3} \text{ GeV}^{-1/2})$$

$$G_{MI} = + [4.460 \pm 0.023 \pm 0.104]$$

$$A_{3/2} = -266.90 \pm 1.62 \pm 7.81 \ (10^{-3} \text{ GeV}^{-1/2})$$

$$Q(\Delta^+) = -[0.182 \pm 0.015 \pm 0.103] \text{ fm}^2$$

proton dipole and spin-polarizabilities :

$$\bar{\alpha} - \bar{\beta} = +10.39 \pm 1.77 {}^{+1.02}_{-1.87} \ (10^{-4} \text{ fm}^3)$$

$$\gamma_\pi = -27.23 \pm 2.27 {}^{+2.24}_{-2.10} \ (10^{-4} \text{ fm}^4)$$

$$\bar{\alpha} + \bar{\beta} = +13.25 \pm 0.86 {}^{+0.23}_{-0.58} \ (10^{-4} \text{ fm}^3)$$

$$\gamma_o = -1.55 \pm 0.15 {}^{+0.03}_{-0.03} \ (10^{-4} \text{ fm}^4)$$

$$\gamma_{13} = +3.94 \pm 0.53 {}^{+0.20}_{-0.18} \ (10^{-4} \text{ fm}^4)$$

$$\gamma_{14} = -2.20 \pm 0.27 {}^{+0.05}_{-0.09} \ (10^{-4} \text{ fm}^4) .$$

Present focus at LEGS:

*beam-target double-polarization experiments
polarized $\vec{\gamma}$ -beams on polarized \vec{p} and \vec{D}*

- Structure of the $n(\gamma, \pi)$ amplitude,
 \Leftrightarrow polarization asymmetries Σ , E and G
 \Leftrightarrow new theoretical effort with Harry Lee

\Rightarrow Nucleon spin sum-rules in $\vec{\gamma} + \vec{N}$:

- forward spin-polarizability SR
(90% energy coverage at LEGS)

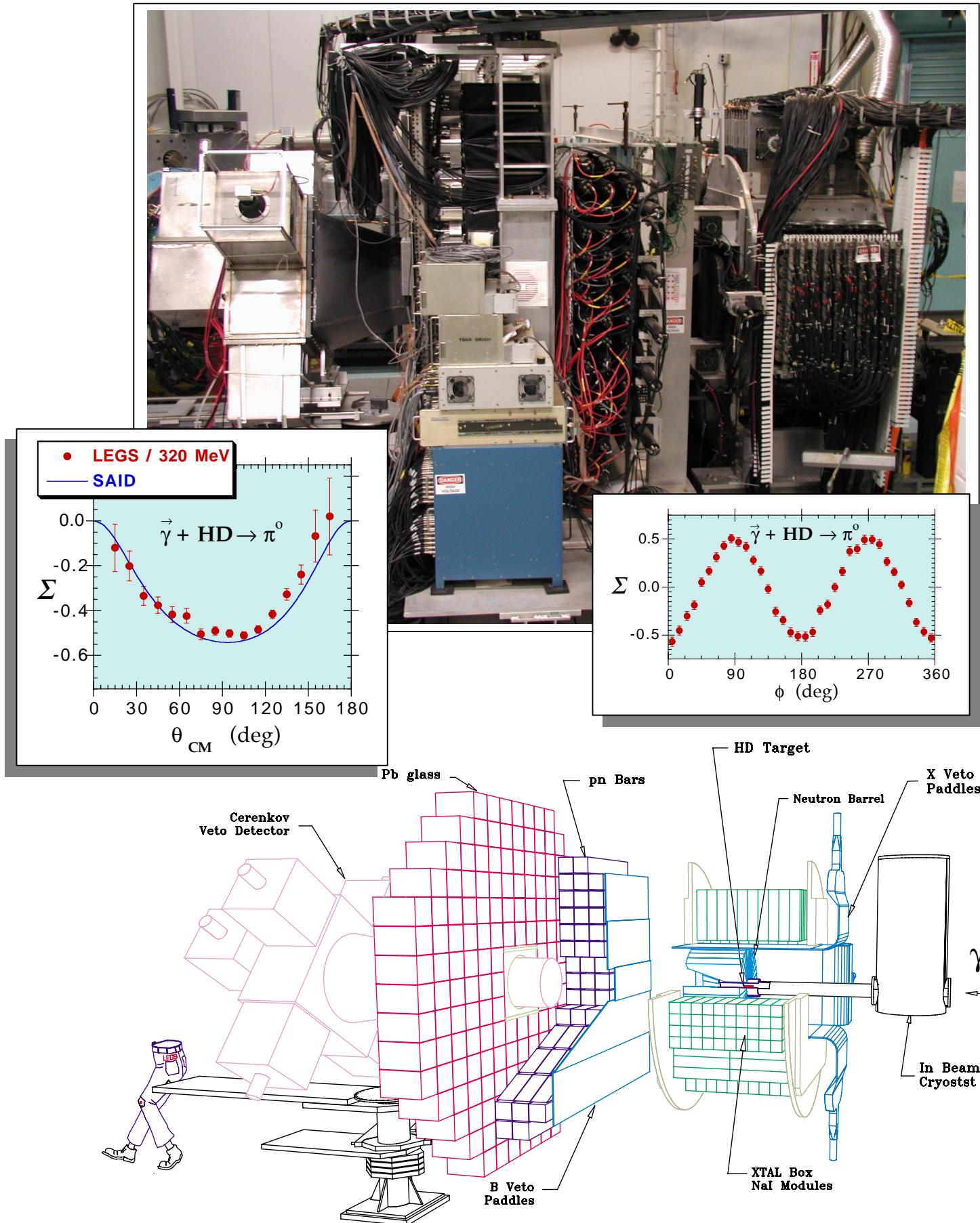
$$\gamma_o = \frac{1}{4\pi^2} \int \frac{\sigma_{anti} - \sigma_{par}}{E_\gamma^3} dE_\gamma$$

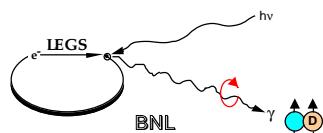
- Gerasimov-Drell-Hearn SR,
(65% energy coverage at LEGS)

$$-(\kappa^2) \frac{2\pi^2 a}{m^2} = \int \frac{\sigma_{anti} - \sigma_{par}}{E_\gamma} dE_\gamma$$

- Nucleon spin-polarizabilities in $\vec{\gamma} + \vec{N} \rightarrow \gamma N$ Compton scattering.
- $\vec{\gamma} + \vec{D} \rightarrow \vec{p}n$ and the N- Δ interaction.

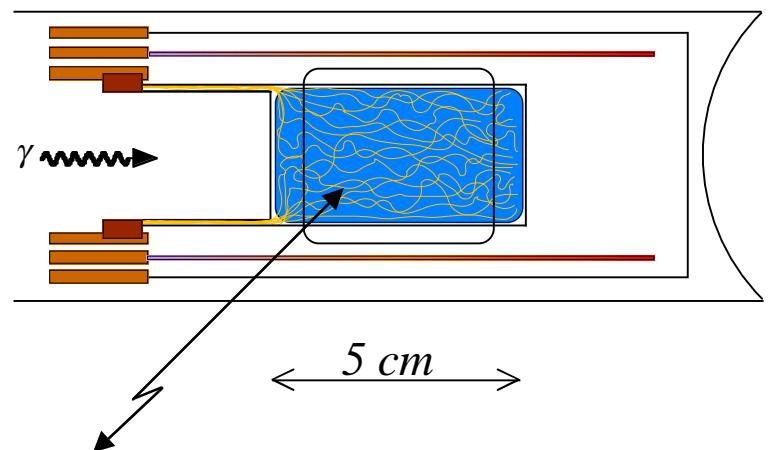
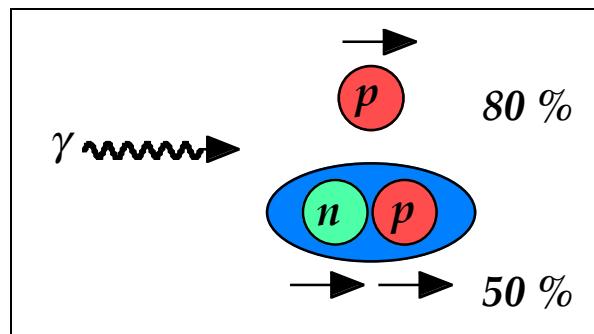
LEGS Spin ASYmmetry array (SASY)



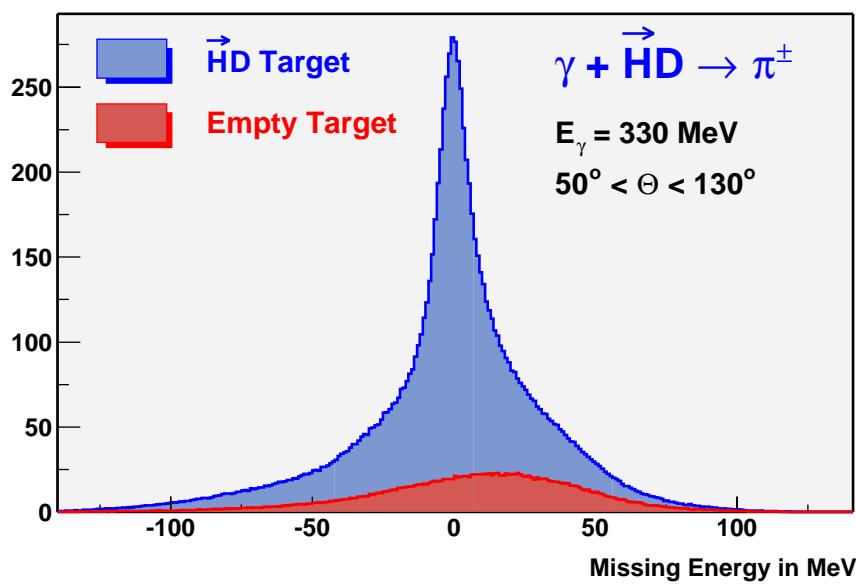


Strongly Polarized Hydrogen-deuteride ICE (SPHICE)

a new class of frozen-spin target for photonuclear experiments

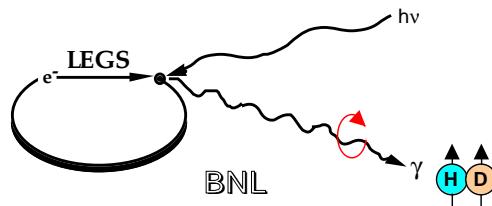


*3 gm solid HD + 20% Al by weight
($2050 \times 50 \mu\text{m}$ wires)*



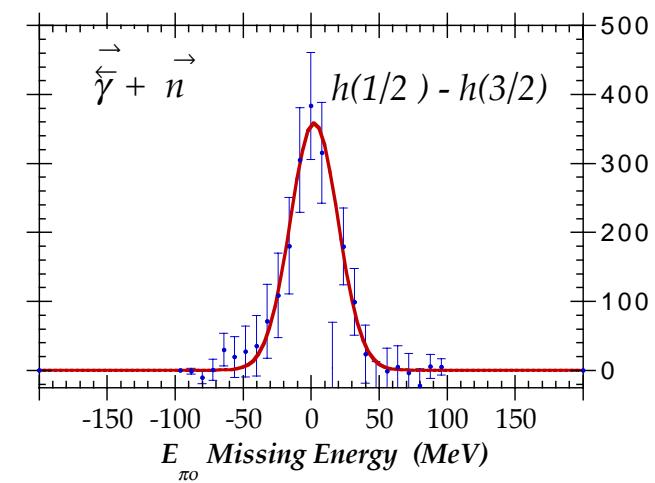
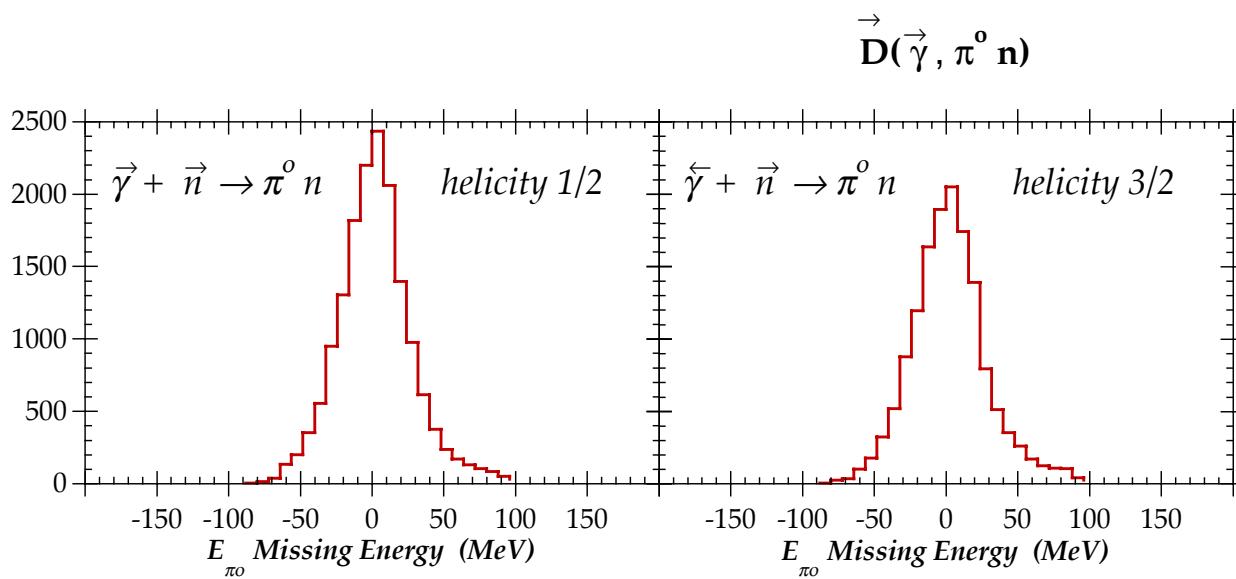
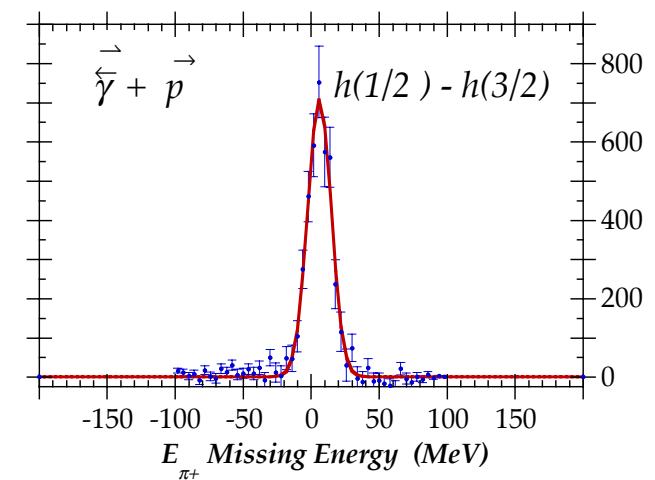
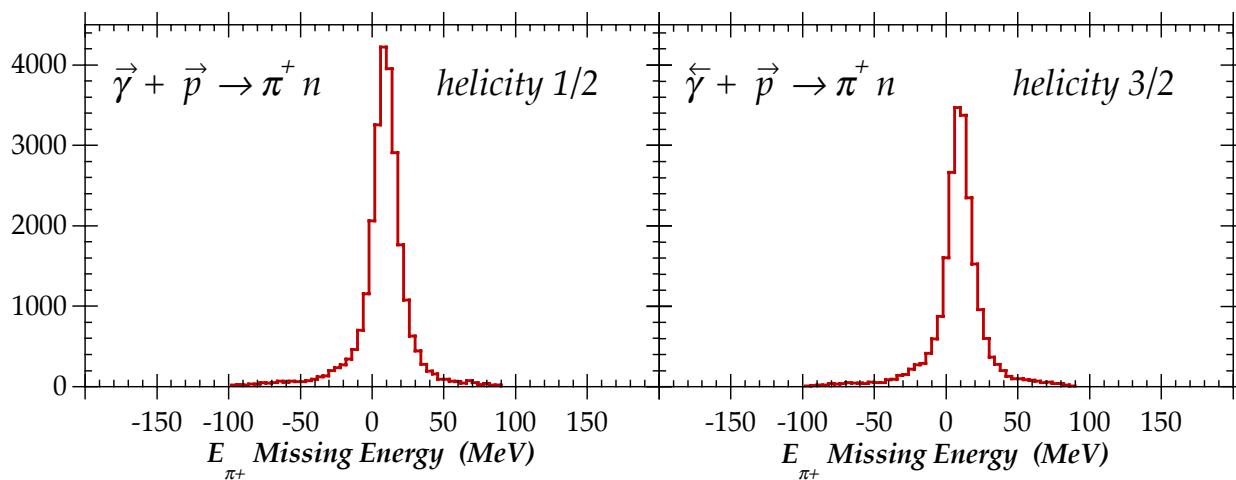
<i>Polarization</i>		
	P_H	P_D
Sept'01	70 %	17 %
Nov'01	30 %	6 %
<i>goal</i>	80 %	50 %

<i>in-beam spin-relaxation</i>		
	T_1^H	T_1^D
Nov'01 (1.3°)	13 d	36 d
<i>goal</i> (0.2°)	>30 d	>100 d



$300 \text{ MeV} < E_\gamma < 350 \text{ MeV}$

$75^\circ < \theta_{\text{CM}} < 105^\circ$

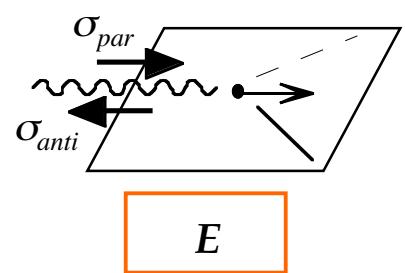
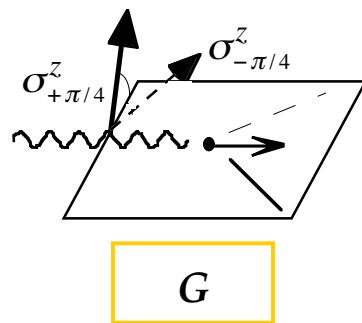
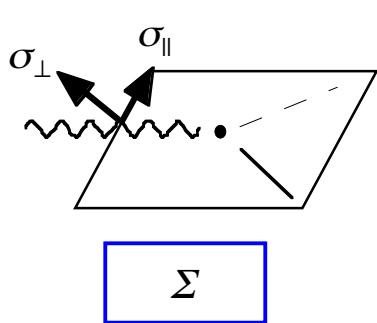


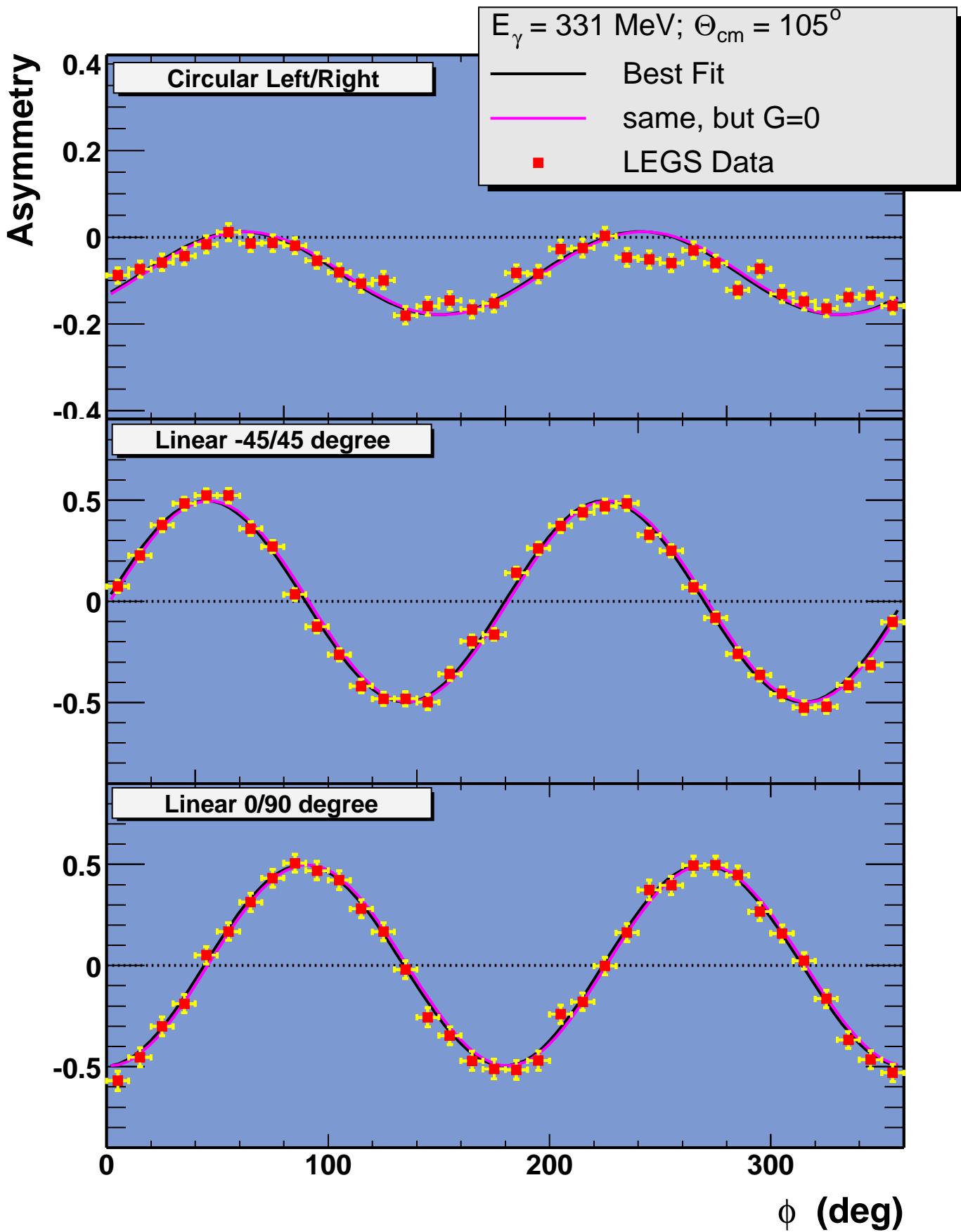
Polarization Observables

- longitudinal target polarization P_z
 - flip between different γ -ray polarization states, at random intervals:
 - left circular*
 - right circular*
 - 0° linear*
 - 90° linear*
 - +45° linear*
 - 45° linear*
 - bremsstrahlung*
- Klein-Nishina*
laser polarization
brem
 ≈ 0.99

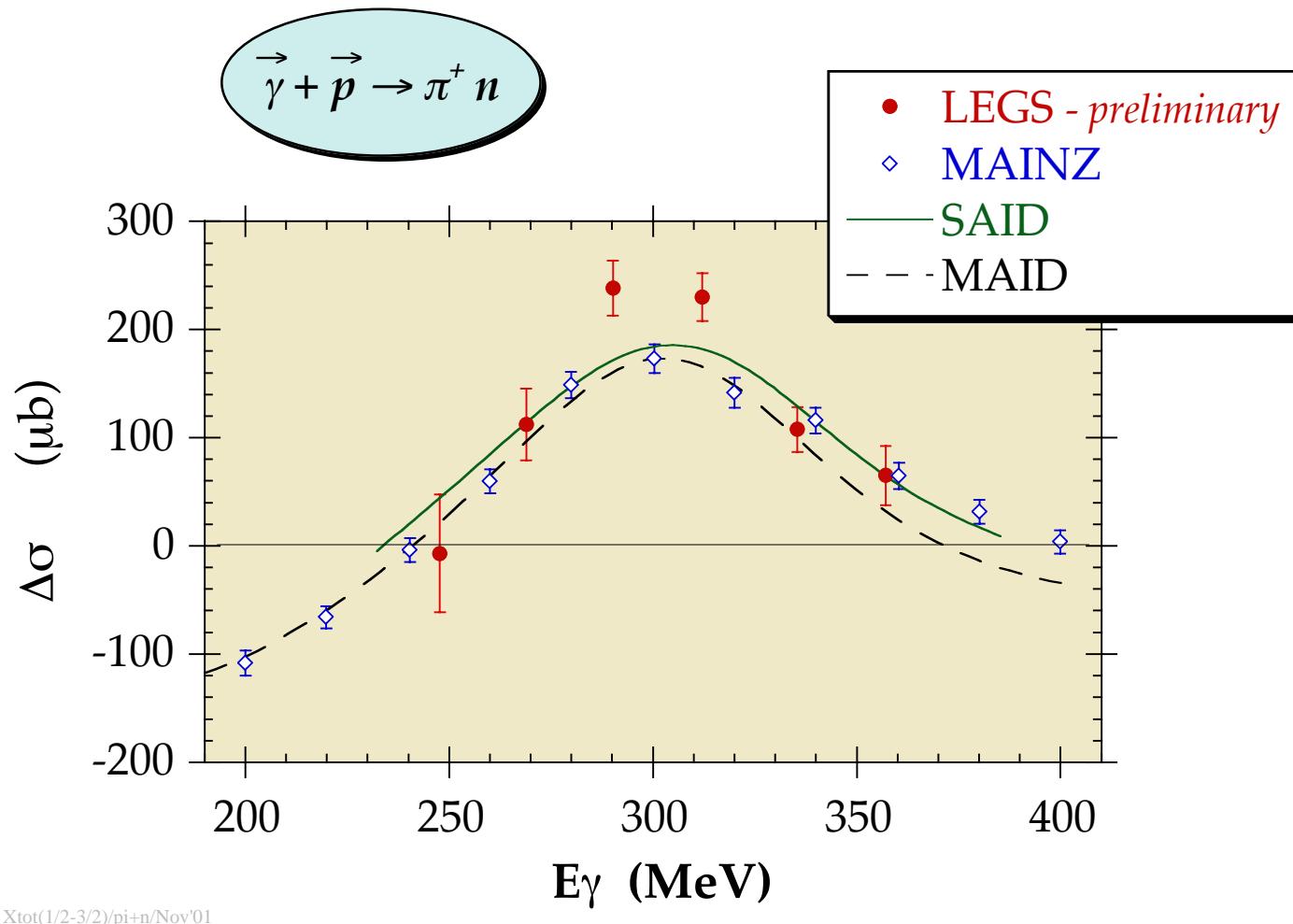
- γ polarization \Leftrightarrow Stokes vector:
$$\left\{ \begin{array}{l} Q_i(E_\gamma) = Q_i^L \cdot \wp_{Linear}(E_\gamma) \cdot P_{brem}, \\ U_i(E_\gamma) = U_i^L \cdot \wp_{Linear}(E_\gamma) \cdot P_{brem}, \\ V_i(E_\gamma) = V_i^L \cdot \wp_{Circular}(E_\gamma) \cdot P_{brem}. \end{array} \right.$$

$$\frac{d\sigma_i}{d\Omega}(\theta, \phi; E_\gamma) = \frac{d\sigma}{d\Omega}(\theta; E_\gamma) \cdot \left\{ \begin{array}{l} 1 + \left[Q_i(E_\gamma) \cdot \Sigma(\theta; E_\gamma) - P_z \cdot U_i(E_\gamma) \cdot G(\theta; E_\gamma) \right] \cdot \cos 2\phi \\ + \left[P_z \cdot Q_i(E_\gamma) \cdot G(\theta; E_\gamma) + U_i(E_\gamma) \cdot \Sigma(\theta; E_\gamma) \right] \cdot \sin 2\phi \\ - P_z \cdot V_i(E_\gamma) \cdot E(\theta; E_\gamma) \end{array} \right\}$$





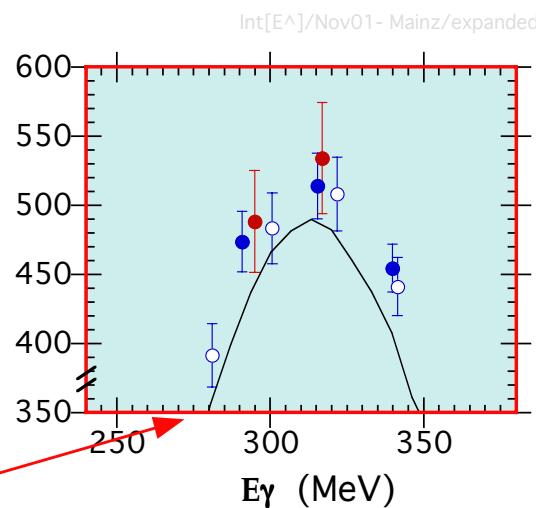
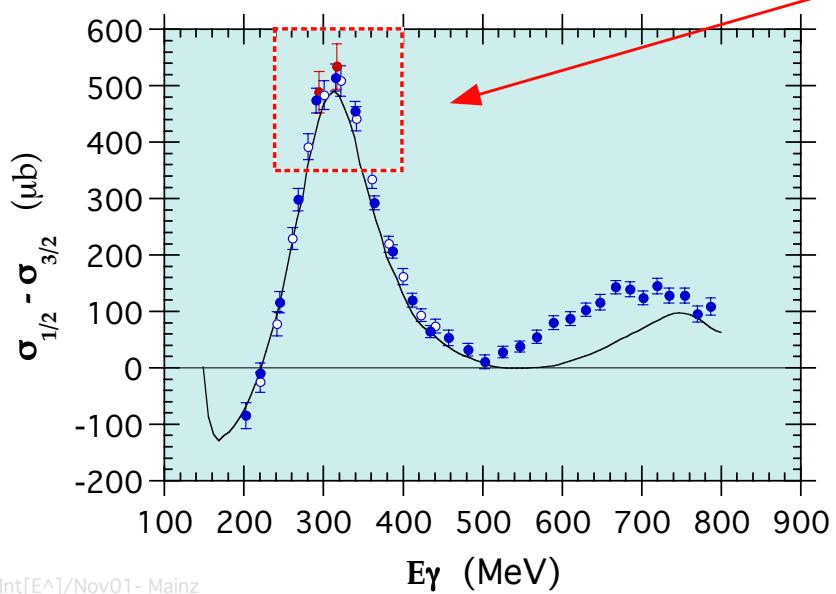
Total helicity difference $\Delta\sigma = \sigma(h=1/2) - \sigma(h=3/2)$



Xtot(1/2-3/2)/pi+n/Nov'01



- LEGS: "Int[E^]/Nov01"
- Mainz: PRL84 (00)
- Mainz: PRL87 (01)
- SAID

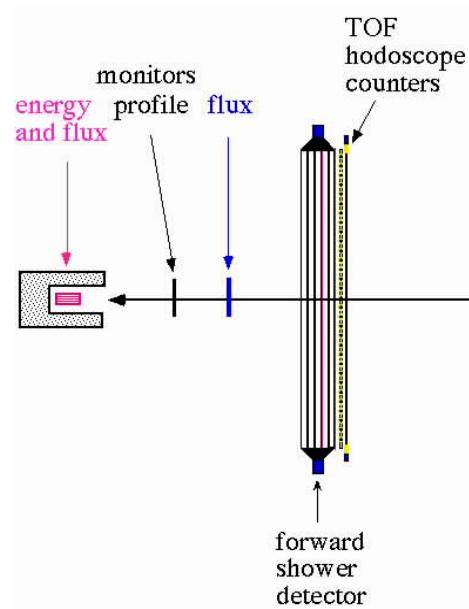


*3.5 days
of data !*

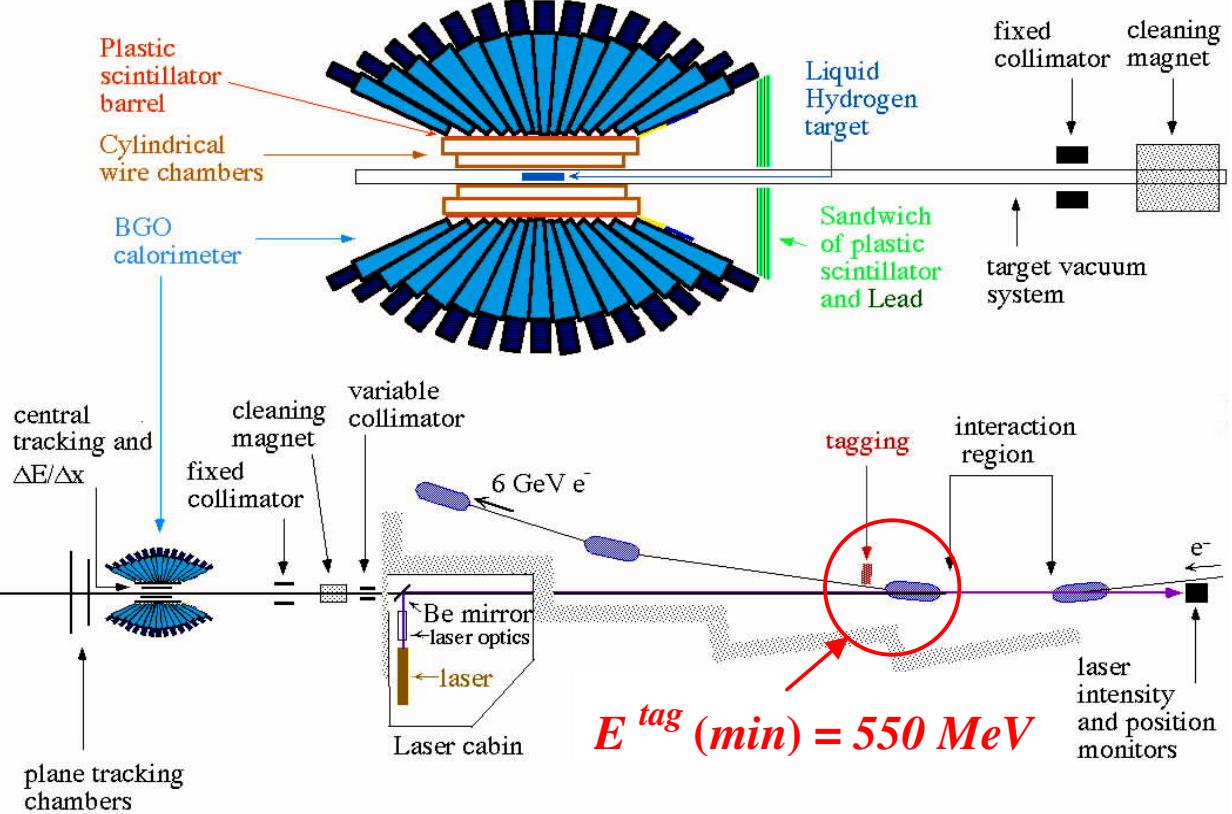
Future reductions in statistical errors:

- × $\sqrt{2}$ from full beam flux
- × 2 from full target polarization
- × $\sqrt{3}$ if measured inclusively

Ar-Ion laser			
$\lambda(\text{nm})$	351	488	515
E_γ (max)	1470 MeV	1136 MeV	1087 MeV

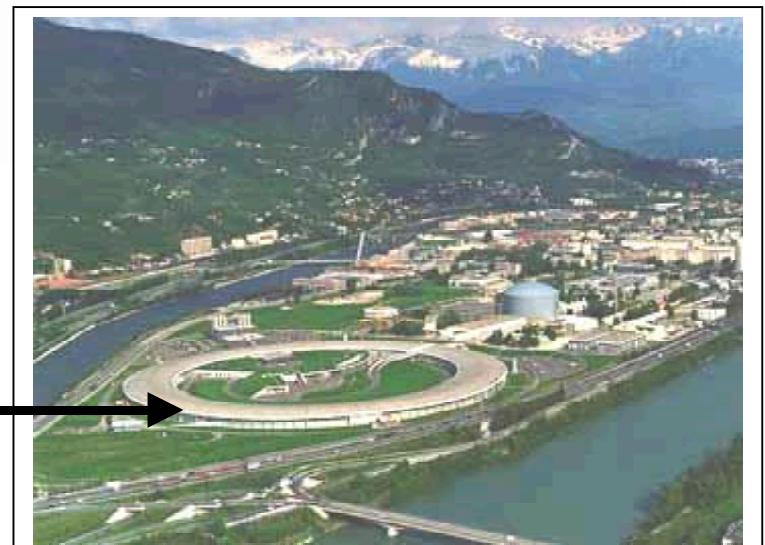


Lagrange detector



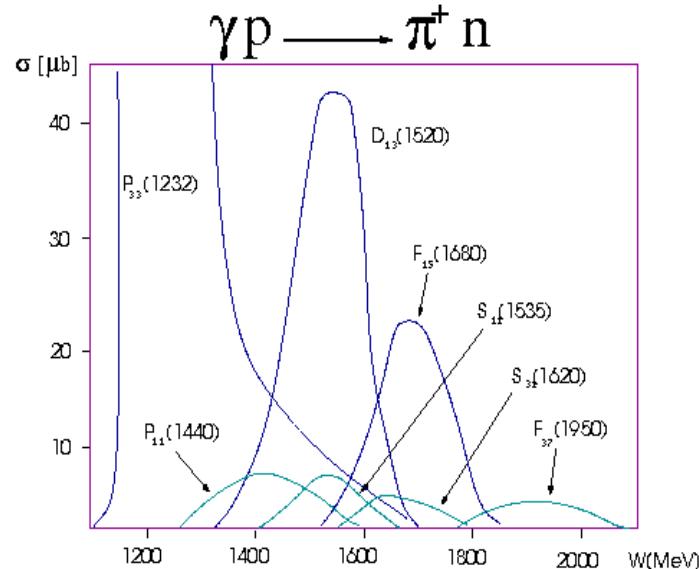
GRenoble-Anneau-Accélération-Laser
(GRAAL)

at the 6 GeV *ESRF*

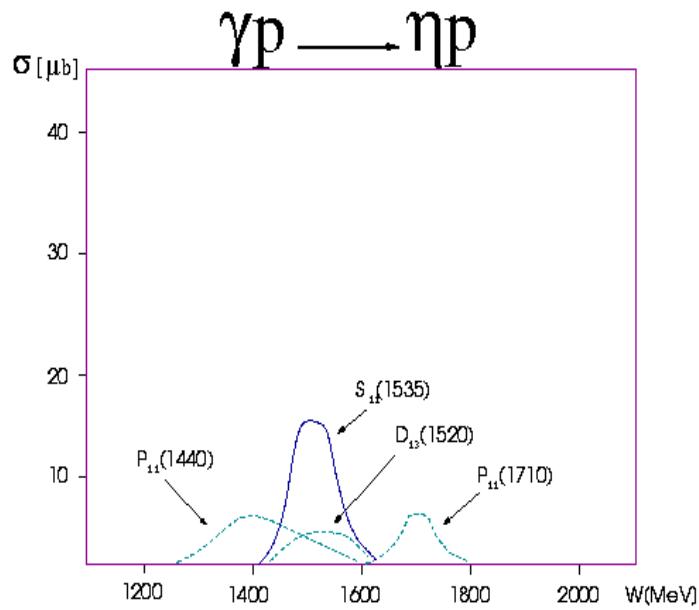


Isospin selection in $\vec{\gamma} + p \rightarrow \eta + p$

$$I = 0 \quad I = 1/2$$



Both N^* and Δ resonances may contribute to the reaction mechanism



Only N^* resonances may contribute to the reaction mechanism

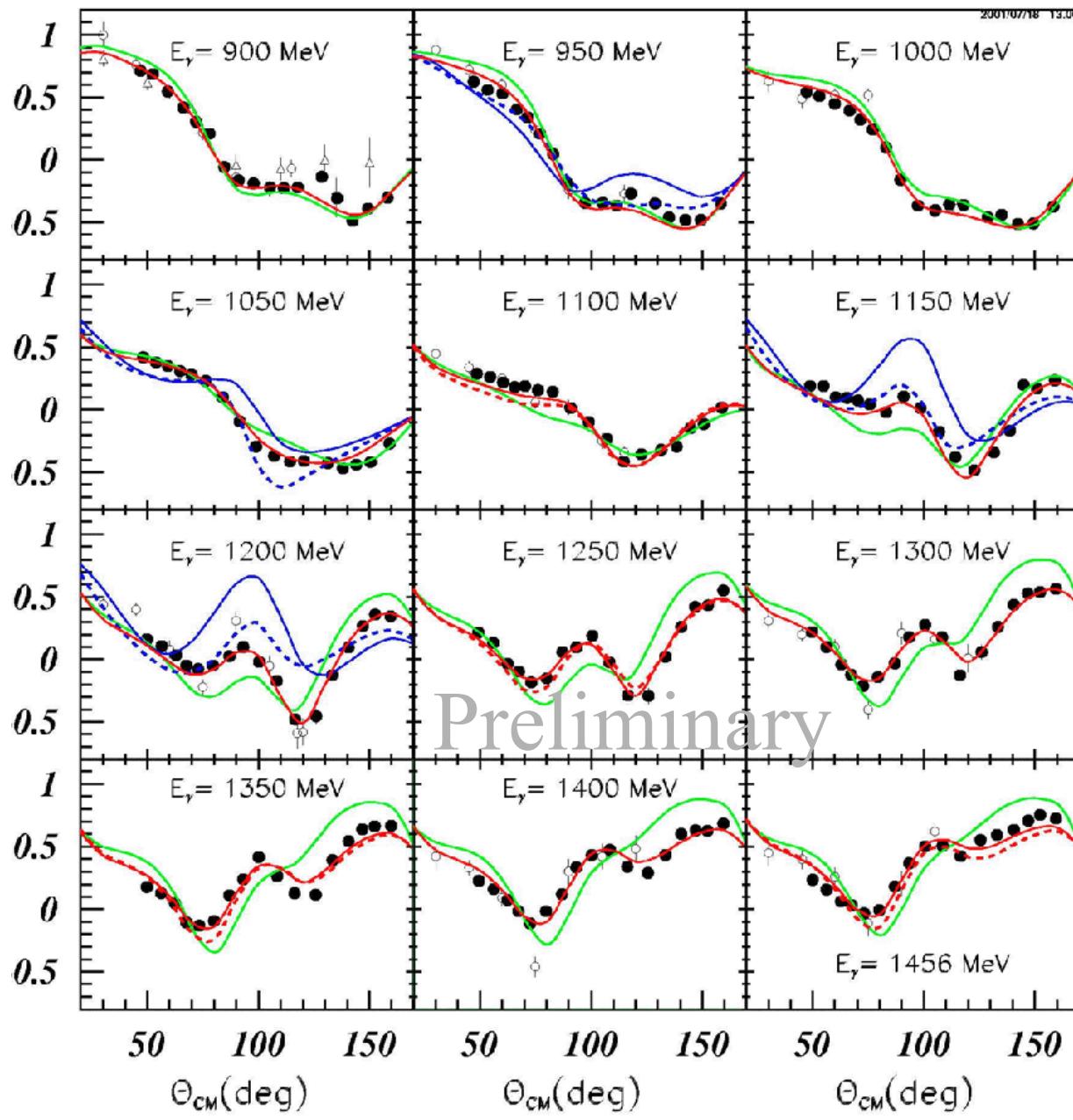
$\vec{\gamma} + p \rightarrow \eta + N$: analyses of GRAAL σ and Σ results

	GRAAL	PDG	Isgur-Karl
$\gamma p \rightarrow S_{11}(1535) \rightarrow \eta N$			
$\Gamma(\text{MeV}) :$	152 ± 4	175 ± 75	252
$\Theta [S_{11}(1535) / S_{11}(1650)] :$	$-31^\circ \pm 2^\circ$		-31.7°

$\gamma p \rightarrow D_{13}(1520) \rightarrow \eta N$			
$\Gamma_{\eta N} / \Gamma :$	$(0.08 \pm 0.01) \%$	$(0.1 \pm 0.2) \%$	0.09%
$\Theta [D_{13}(1520) / D_{13}(1700)] :$	$+10^\circ \pm 2^\circ$		$+6.3^\circ$

$\gamma p \rightarrow F_{15}(1680) \rightarrow \eta N$			
$\Gamma_{\eta N} / \Gamma :$	0.15% $+0.35/-0.10 \%$	$(1.0 \pm 0.4) \%$	0.8%

Phys. Rev. D**60**, (1999), 052004; Phys Rev. C**60**, (1999), 35210; Eur. Phys. J., A**11**, (2001), 217



data
 black circles - new Graal data
 open circles - Daresbury (1979)
 open triangles - SLAC (1974)

curves
 green solid - SAID WI00
 red dashed - SAID SP01
 red solid - SAID FA01
 blue dashed - MAID
 (benchmark database)
 blue solid - MAID 2000

Born, vector meson exchange,
 $P_{33}(1232), P_{11}(1440), D_{13}(1520),$
 $S_{11}(1535), S_{31}(1620), S_{11}(1650),$
 $F_{15}(1680), D_{13}(1700)$

Extracted SAID multipoles

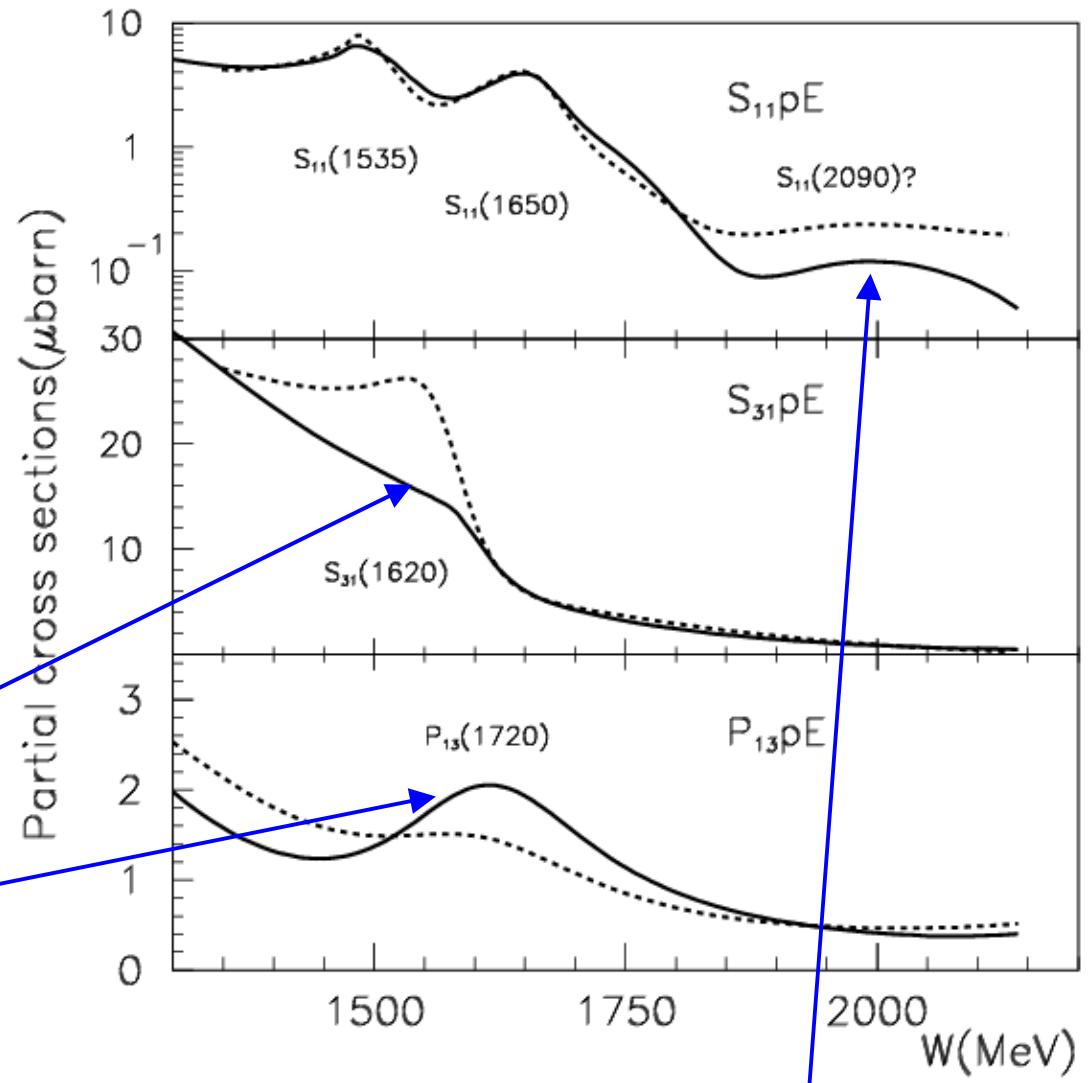
Solution $\chi^2 \pi^+ n(\Sigma)$ overall χ^2

SP00 1047/237 33928/17047
(dashed line)

FA01 555/23 34664/17374
solid line (with new GRAAL data)

The new data analysis shows

- suppression of $S_{31}(1620)$
- presence of the $P_{13}(1720)$
- possible evidence of a third $S_{11}(2090)$ resonance



Meson photo-production at GRAAL

- photocouplings to N^*/Δ resonance
- searching for missing resonances

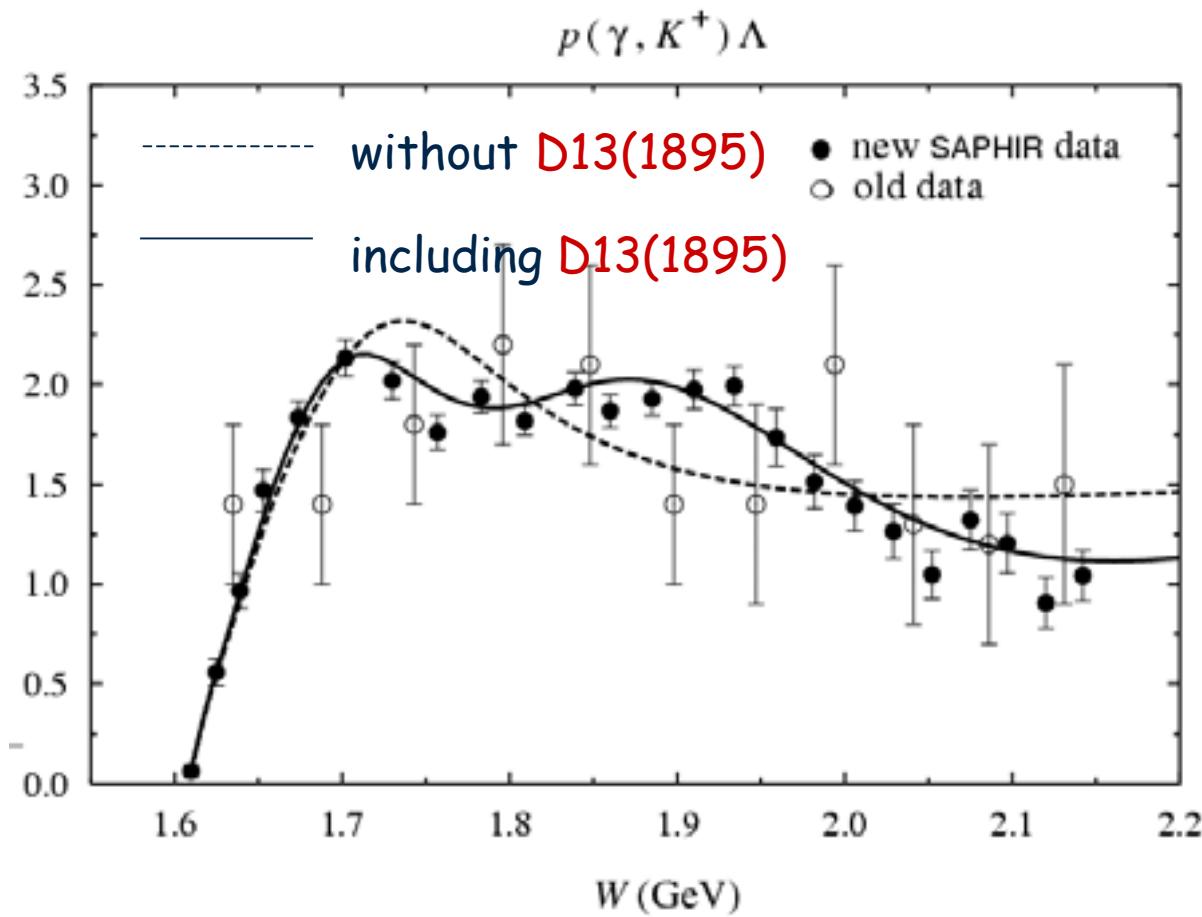
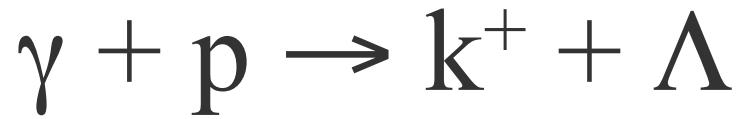
Symmetric CQM models predict more states than the observed ones.

- The “missing” states do not exist (di-quark models)
- The “missing” states have not been observed in reactions where Resonances couple to the πN channel.

N^*	Status	$SU(6) \otimes O(3)$	Parity	Δ^*	Status	$SU(6) \otimes O(3)$
P11(938)	****	(56,0 ⁺)	+	P33(1232)	****	(56,0 ⁺)
S11(1535)	****	(70,1 ⁻)		S31(1620)	****	(70,1 ⁻)
S11(1650)	****	(70,1 ⁻)		D33(1700)	****	(70,1 ⁻)
D13(1520)	****	(70,1 ⁻)	-			
D13(1700)	***	(70,1 ⁻)				
D15(1675)	****	(70,1 ⁻)				
P11(1520)	****	(56,0 ⁺)		P31(1875)	****	(56,2 ⁺)
P11(1710)	***	(70,0 ⁺)		P31(1835)		(70,0 ⁺)
P11(1880)		(70,2 ⁺)				
P11(1975)		(20,1 ⁺)				
P13(1720)	****	(56,2 ⁺)		P33(1600)	***	(56,0 ⁺)
P13(1870)	*	(70,0 ⁺)		P33(1920)	***	(56,2 ⁺)
P13(1910)		(70,2 ⁺)	+	P33(1985)		(70,2 ⁺)
P13(1950)		(70,2 ⁺)				
P13(2030)		(20,1 ⁺)				
F15(1680)	****	(56,2 ⁺)		F35(1905)	****	(56,2 ⁺)
F15(2000)	**	(70,2 ⁺)		F35(2000)	**	(70,2 ⁺)
F15(1995)		(70,2 ⁺)				
F17(1990)	**	(70,2 ⁺)		F37(1950)	****	(56,2 ⁺)

$SU(6) \otimes O(3)$ Super-multiplets assignments

Boxes are consistent with di-quark model



Extracted mass and width are
 $M=1895$ MeV and $\Gamma = 372$ MeV

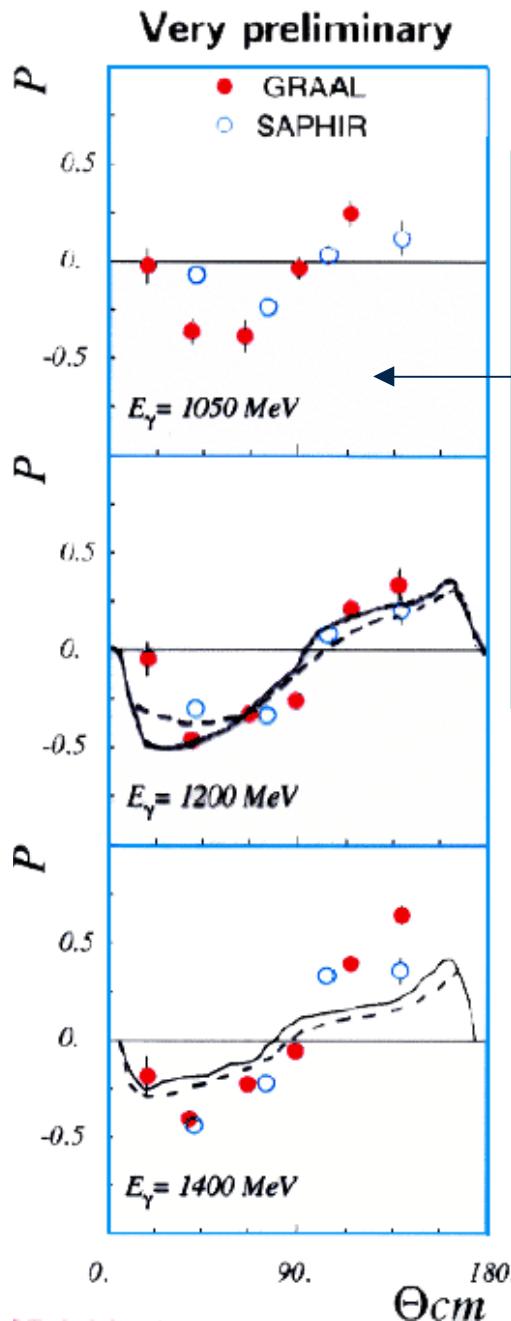
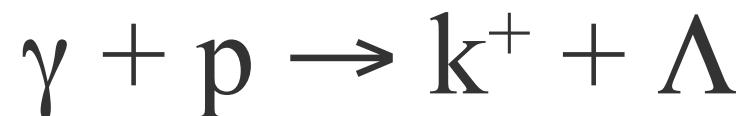
SAPHIR data show a structure in the $k^+\Lambda$ channel at $W=1900$ MeV
M.Q.Tran PLB 445(1998)20

Coupled-channel analysis finds that $S_{11}(1650)$, $P_{11}(1710)$ and $P_{13}(1720)$ have the most significant decay widths in the $k^+\Lambda$ channel

T. Feuster and U. Mosel PRC 57 (1998), 457

Isobar model by C. Bennhold and collaborators, requires the inclusion of a "missing" $D_{13}(1960)$ resonance to reproduce the cross section data.

more data from SAPHIR and SPRING8

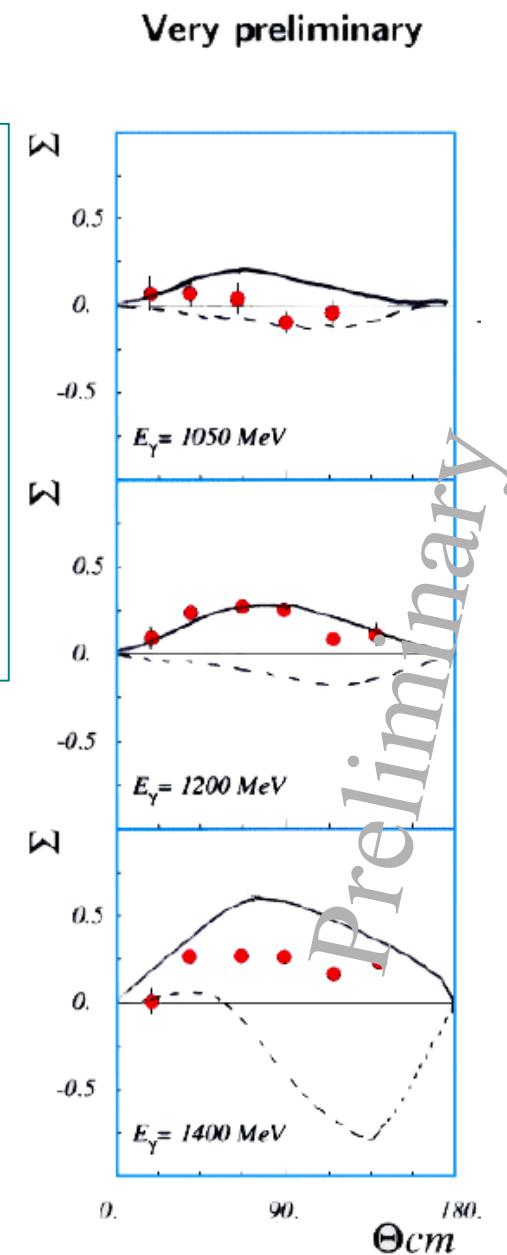


The recoil polarization asymmetry P may be measured from the angular distribution of the $\Lambda \rightarrow p\pi^-$ weak-decay.

Results are available from SAPHIR and GRAAL. They are in agreement, but the observable is not quite sensitive to the inclusion of the "missing" $D_{13}(1960)$

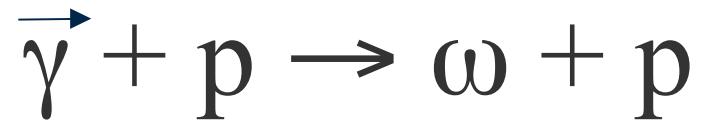
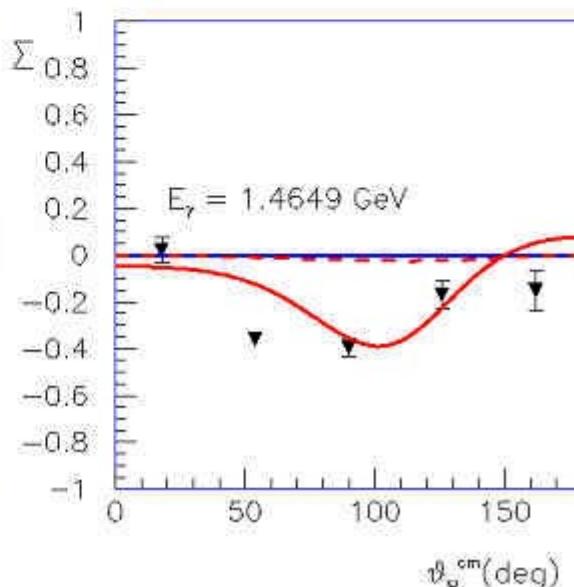
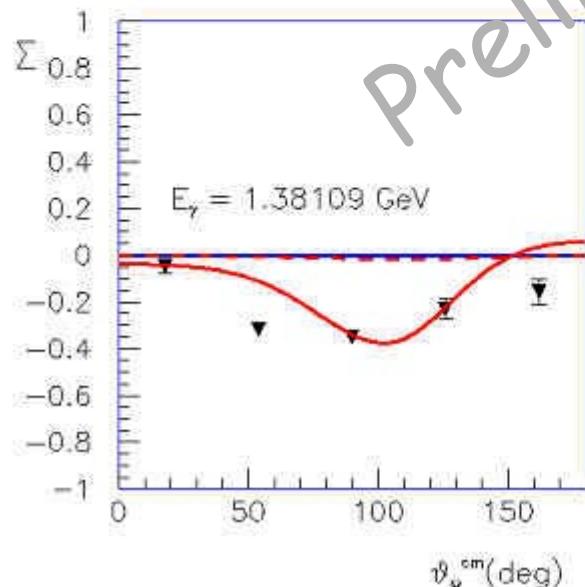
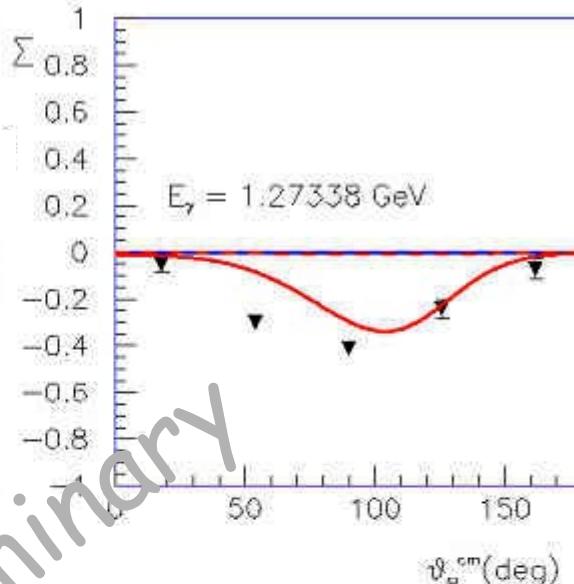
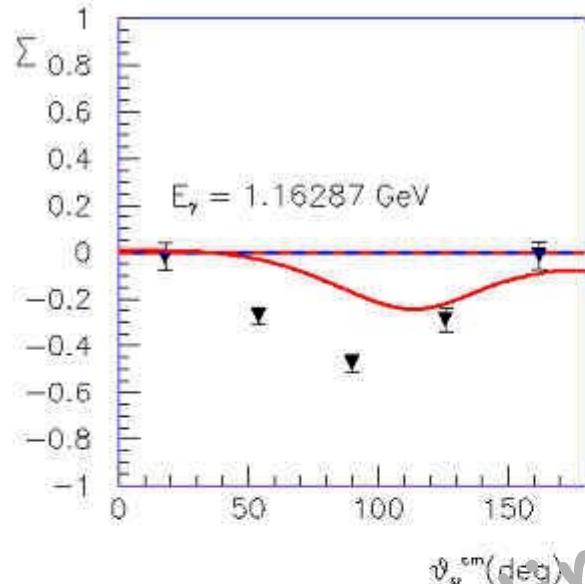
The beam polarization asymmetry Σ is on the contrary very sensitive to the inclusion of the "missing" resonance. The model predict a change of sign in the observable.

First preliminary data on Σ from GRAAL confirm the presence of the resonance





Beam asymmetry Σ



The beam asymmetry Σ is very sensitive to the inclusion of the N^* resonances.

The inclusion of the diffractive t-exchange terms alone produces no asymmetry.

First preliminary results from GRAAL.

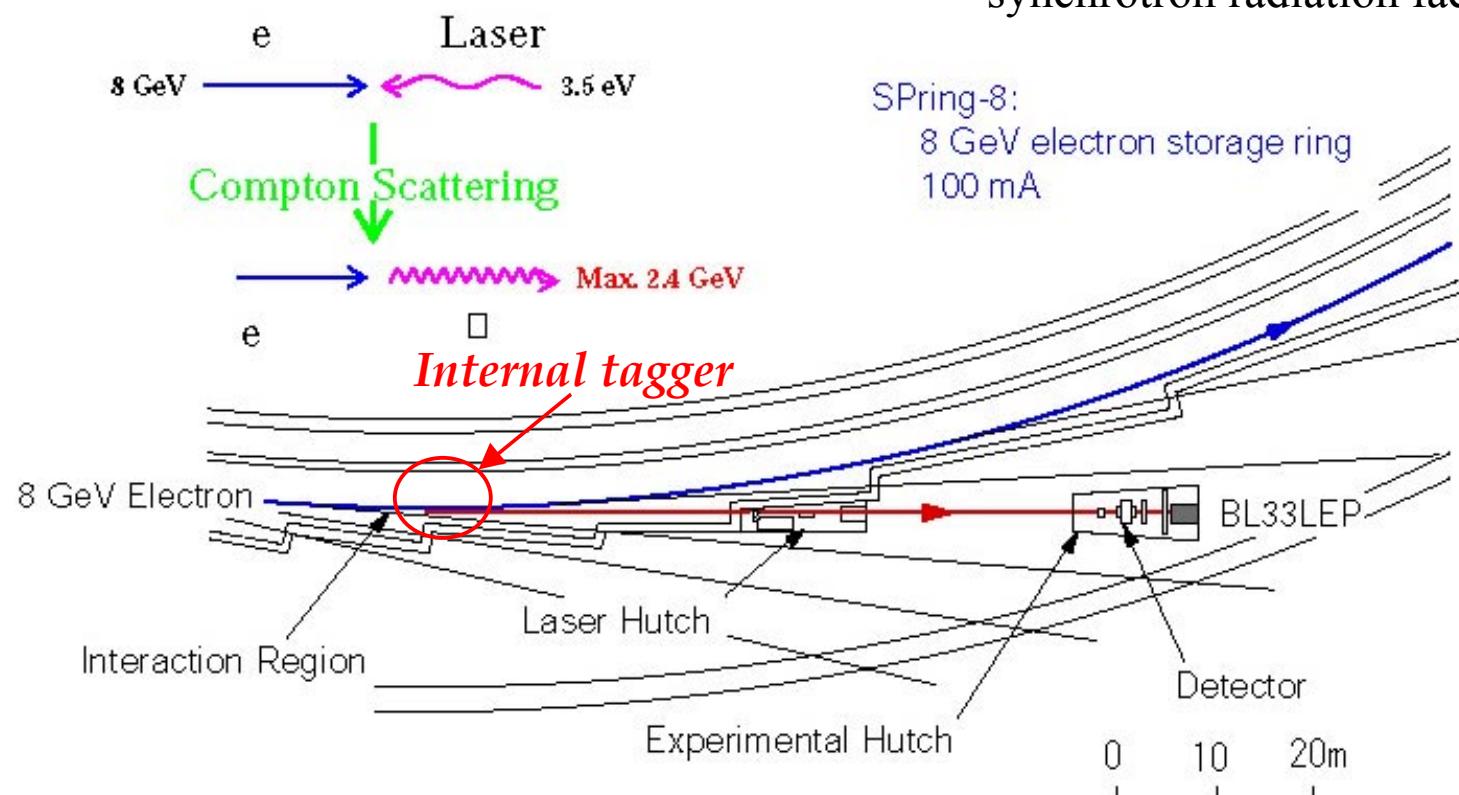
Sizable contribution from N^* resonances.

Model from Zhao includes
 $P_{11}(1440)$, $S_{11}(1535)$, $D_{13}(1520)$,
 $P_{13}(1720)$, $F_{15}(1680)$, $P_{13}(1900)$,
 $F_{15}(2000)$

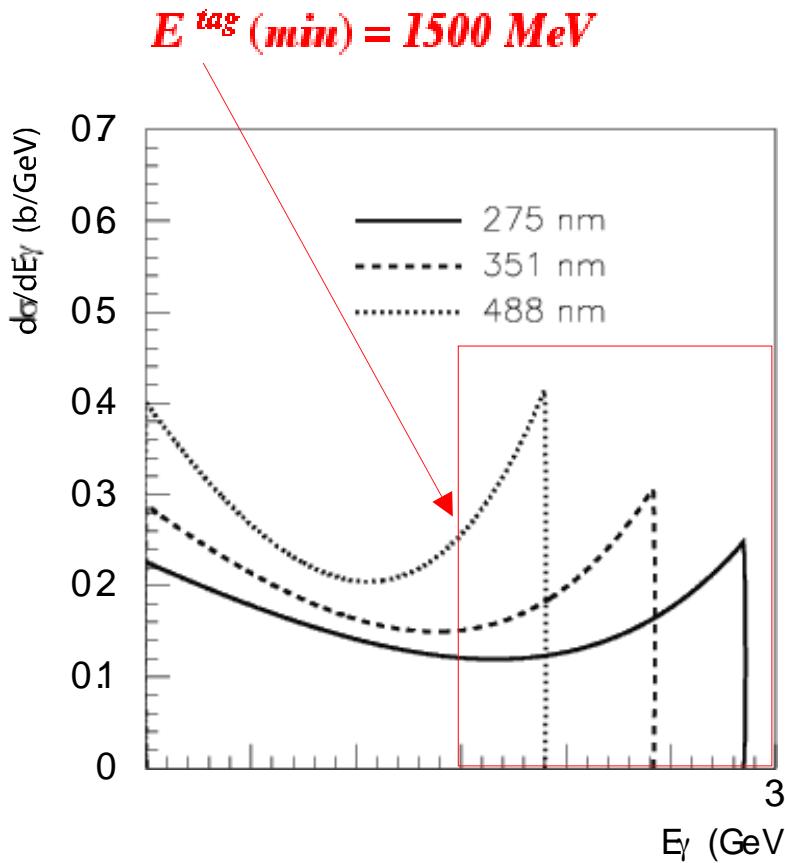
The Laser-Electron Photon Source (*LEPS*) at *SPring-8* (Super Photon ring-8 GeV)



Third-generation
synchrotron radiation facility

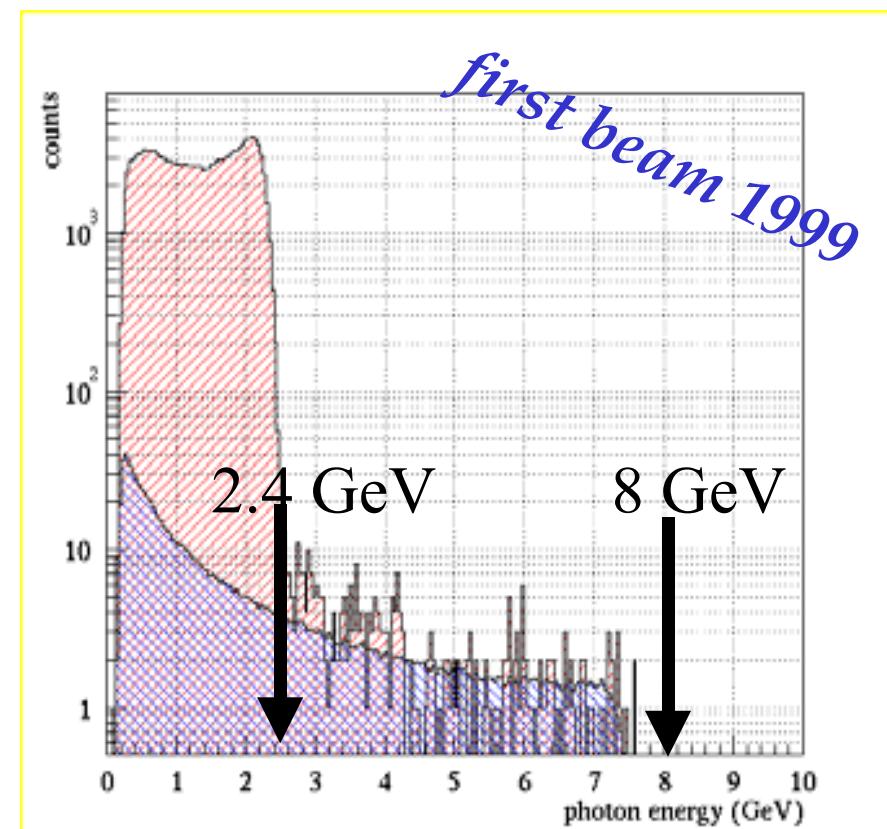


	Ar-Ion laser		
$\lambda(\text{nm})$	300	351	488
E_{γ}	2690	2417	1899
(max)	MeV	MeV	MeV

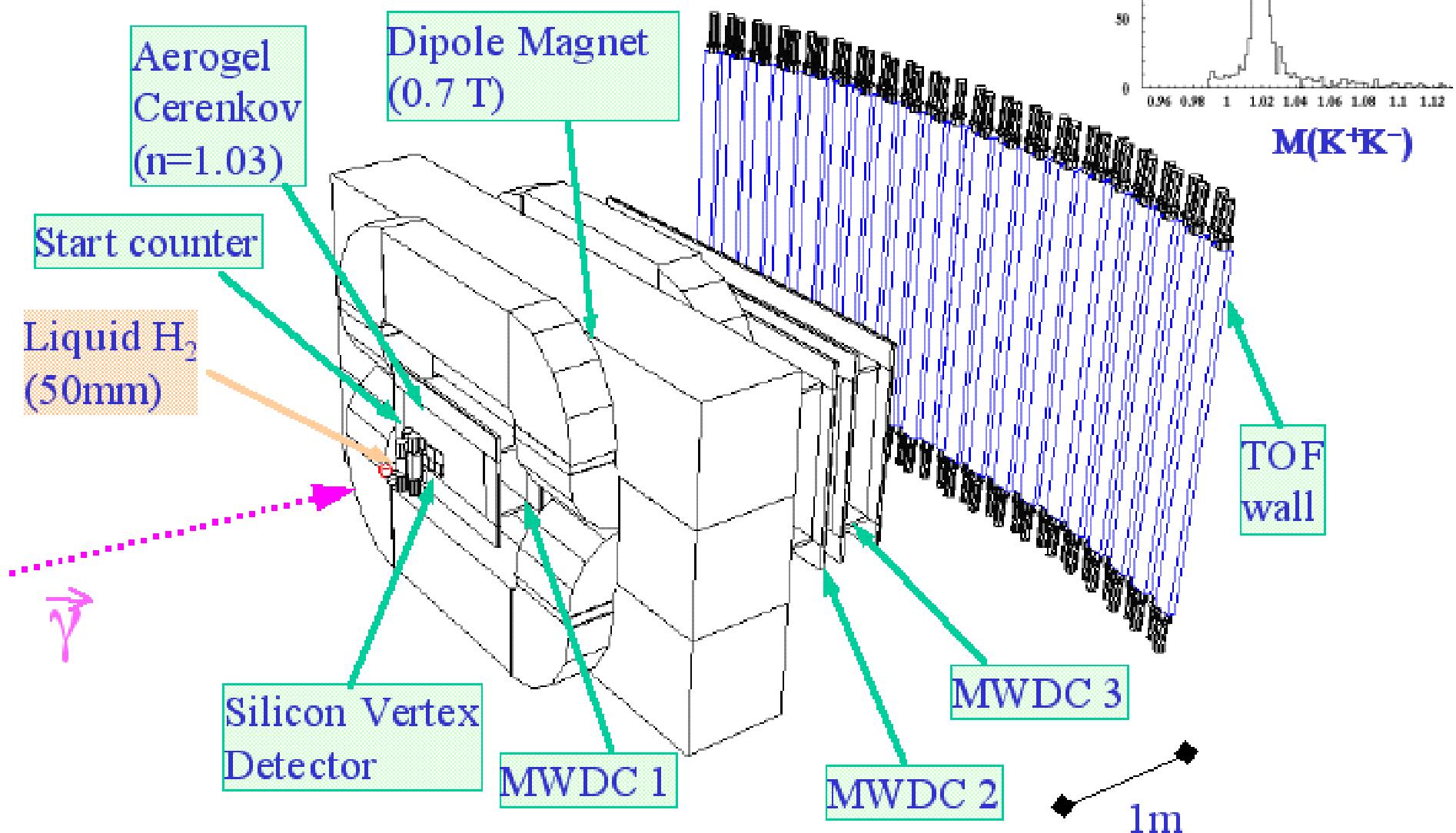


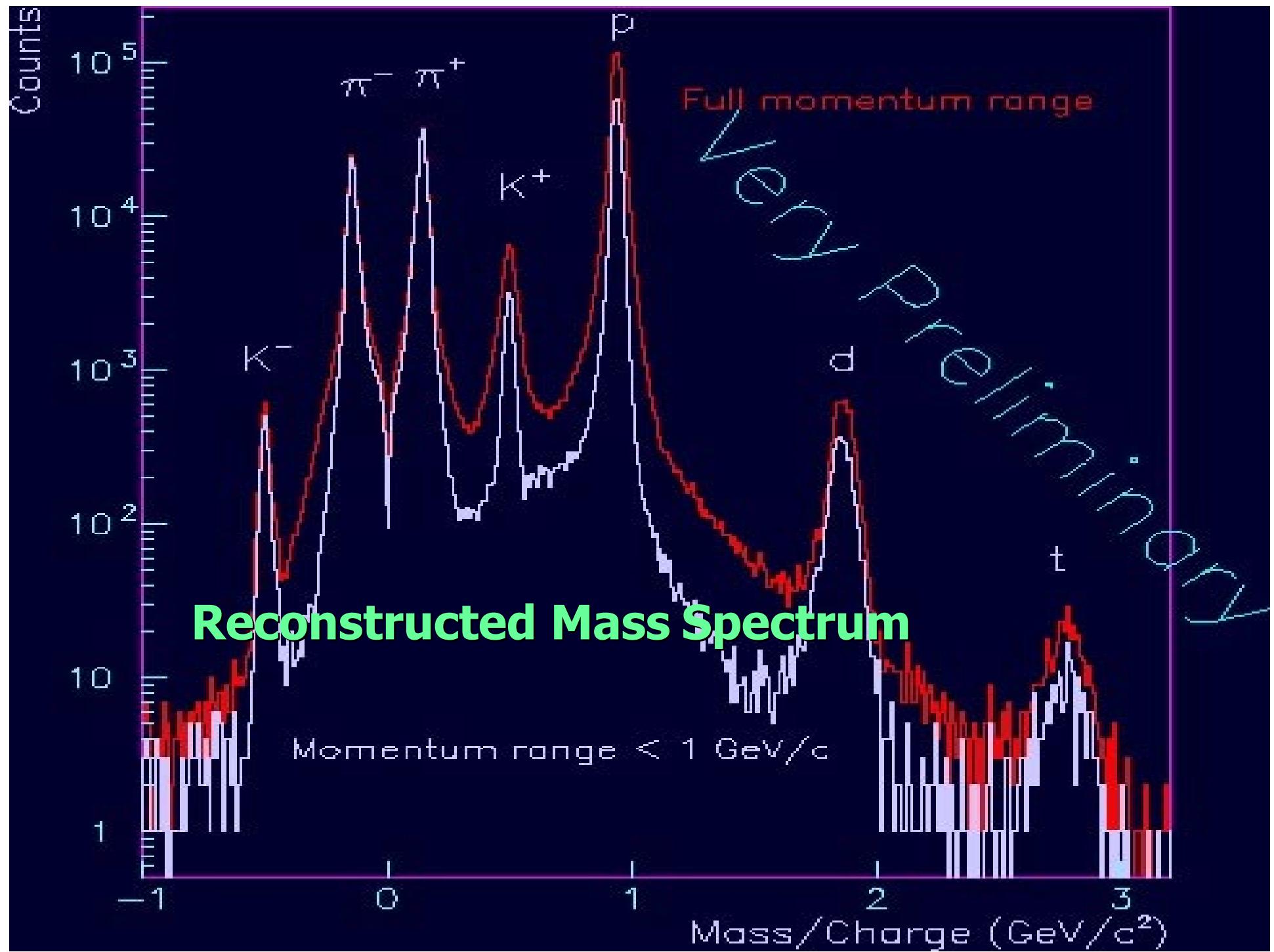
Energy Spectrum

Intensity (Typ.)
 $2.5 * 10^6 \text{ photons/sec}$

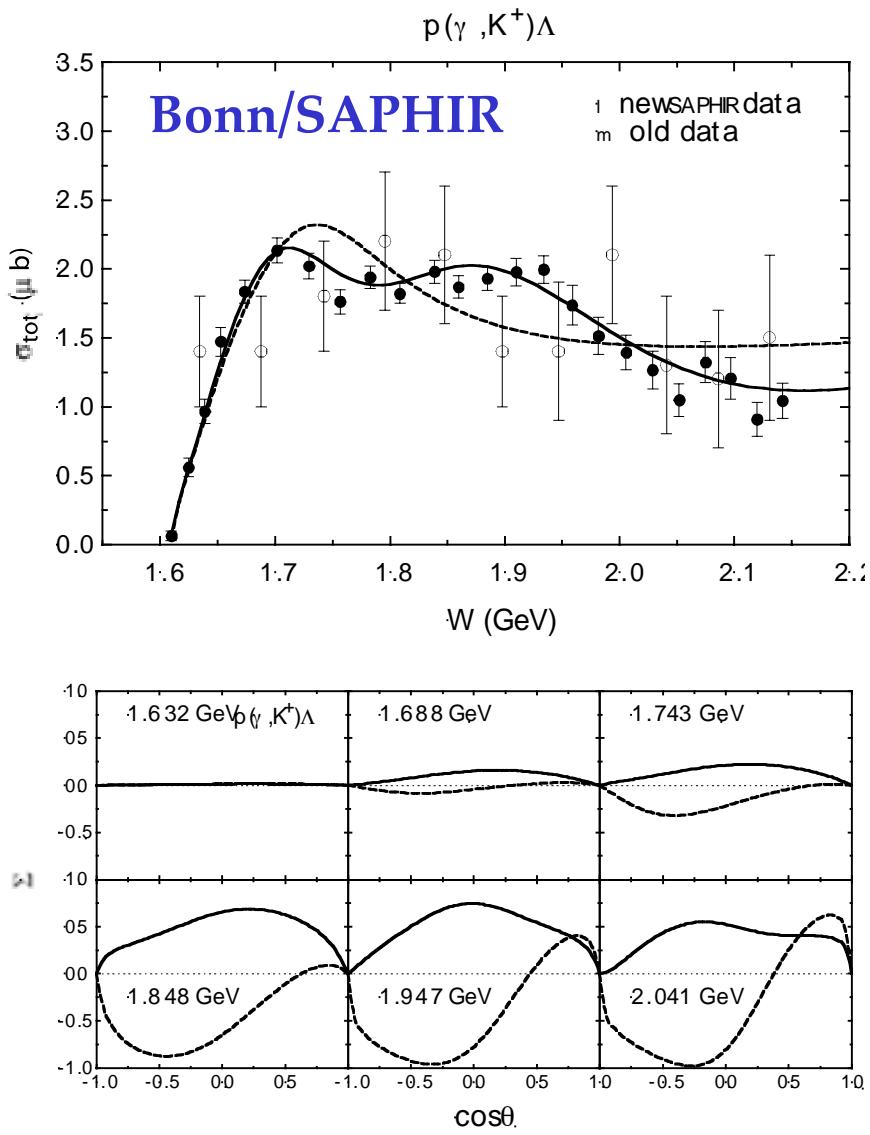


LEPS detector

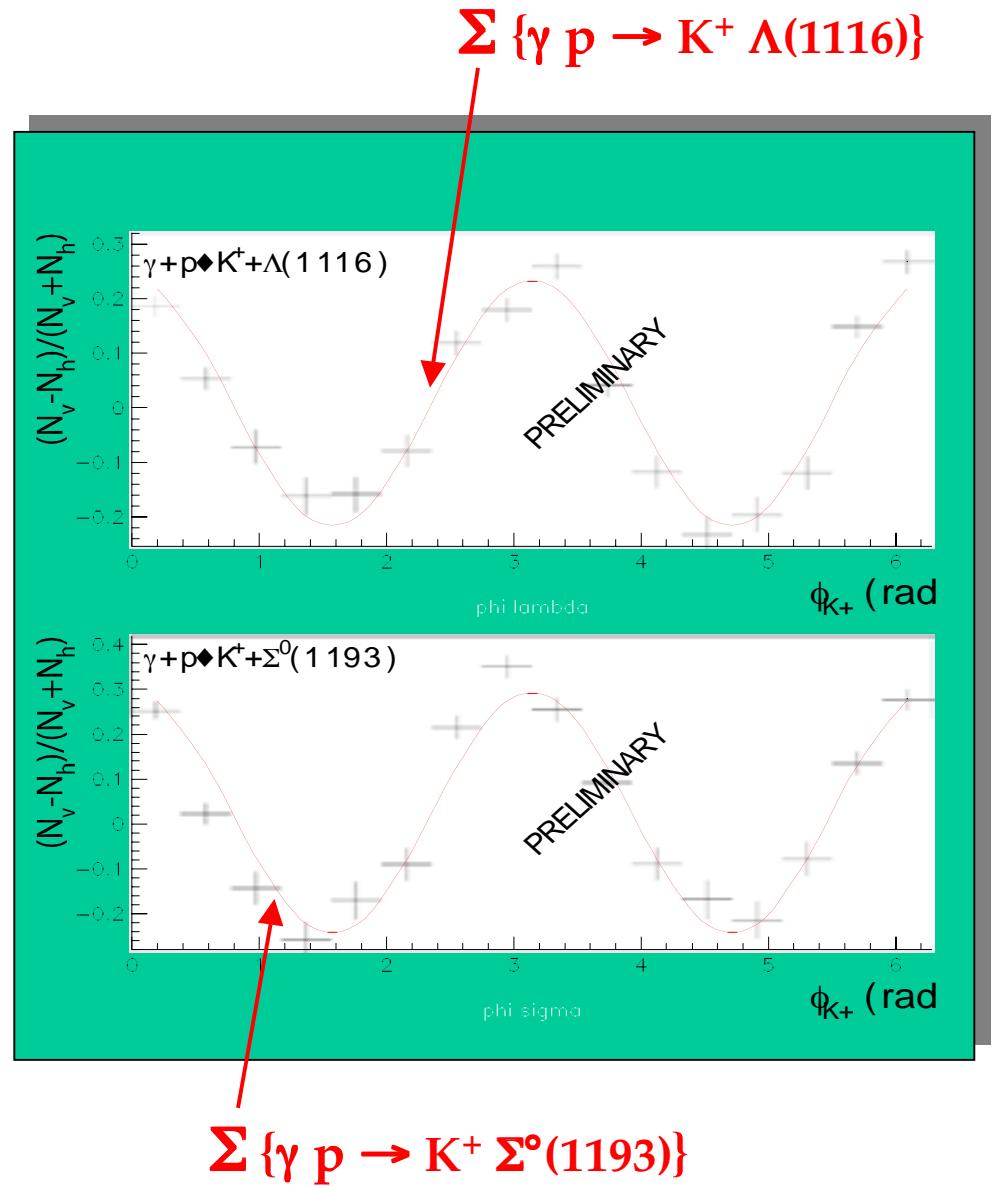




K^+ Photo-production:



Beam Asymmetry \Rightarrow Missing resonance



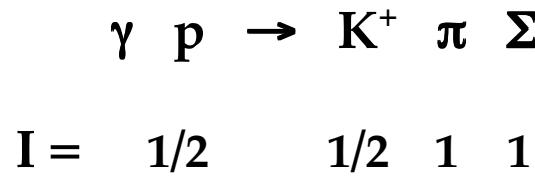
T. Mart and C. Bennhold, PR C61, (R)012201 (2000)

The Nature of the $\Lambda(1405)$?

- uds g hybrid ?
- SU(3) – singlet 3q state ?

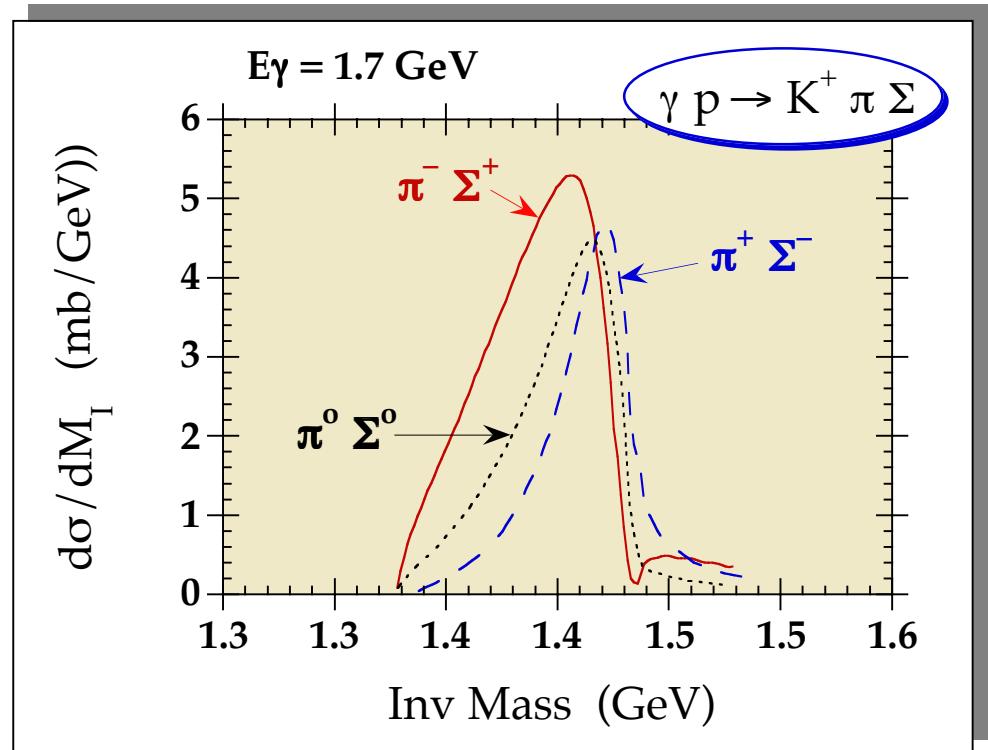
- sub-threshold KN bound state ?*

Nacher, Oset, Toki, Ramos
 Phys. Lett. B 455 (1999) 55
 $(\chi$ Lagrangians + mB FSI + cc)



$$\frac{d\sigma(\pi^+\Sigma^-)}{dM_I} \propto \frac{1}{2}|T^{(1)}|^2 + \frac{1}{3}|T^{(o)}|^2 + \frac{2}{\sqrt{6}}\Re e\left(T^{(o)}T^{(1)*}\right) + \Theta(T^{(2)})$$

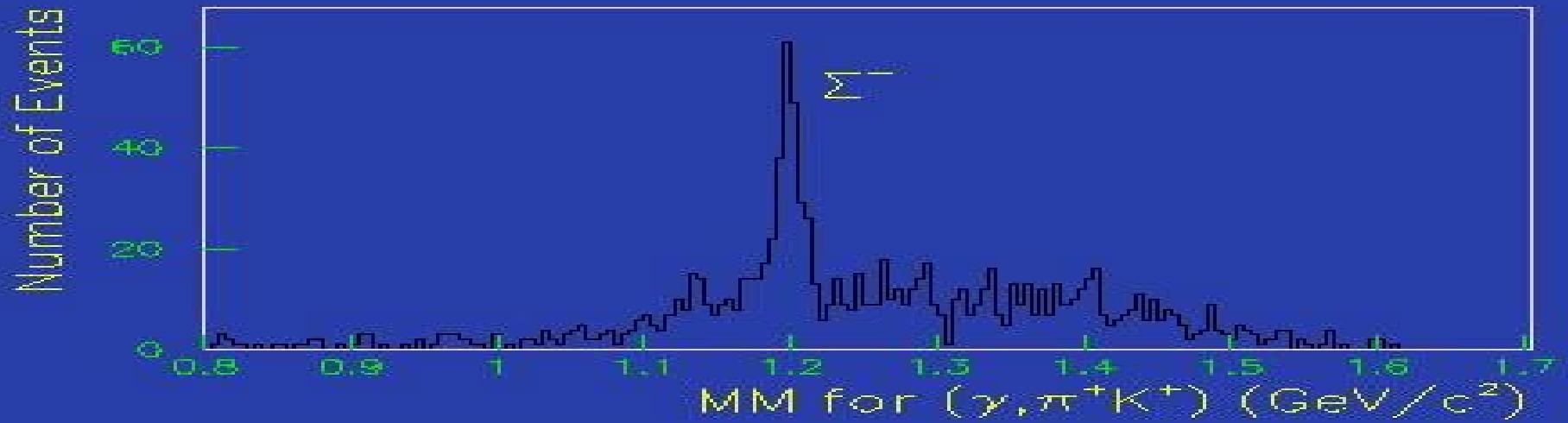
$$\frac{d\sigma(\pi^-\Sigma^+)}{dM_I} \propto \frac{1}{2}|T^{(1)}|^2 + \frac{1}{3}|T^{(o)}|^2 - \frac{2}{\sqrt{6}}\Re e\left(T^{(o)}T^{(1)*}\right) + \Theta(T^{(2)})$$

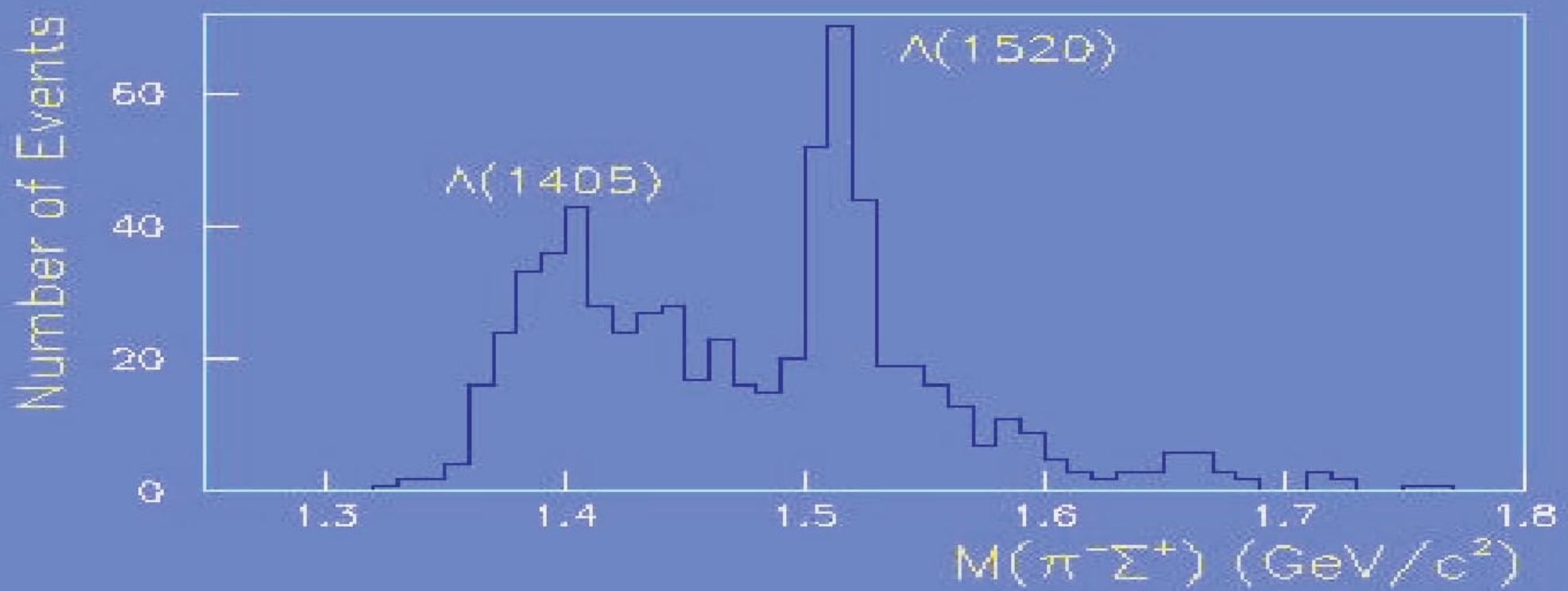
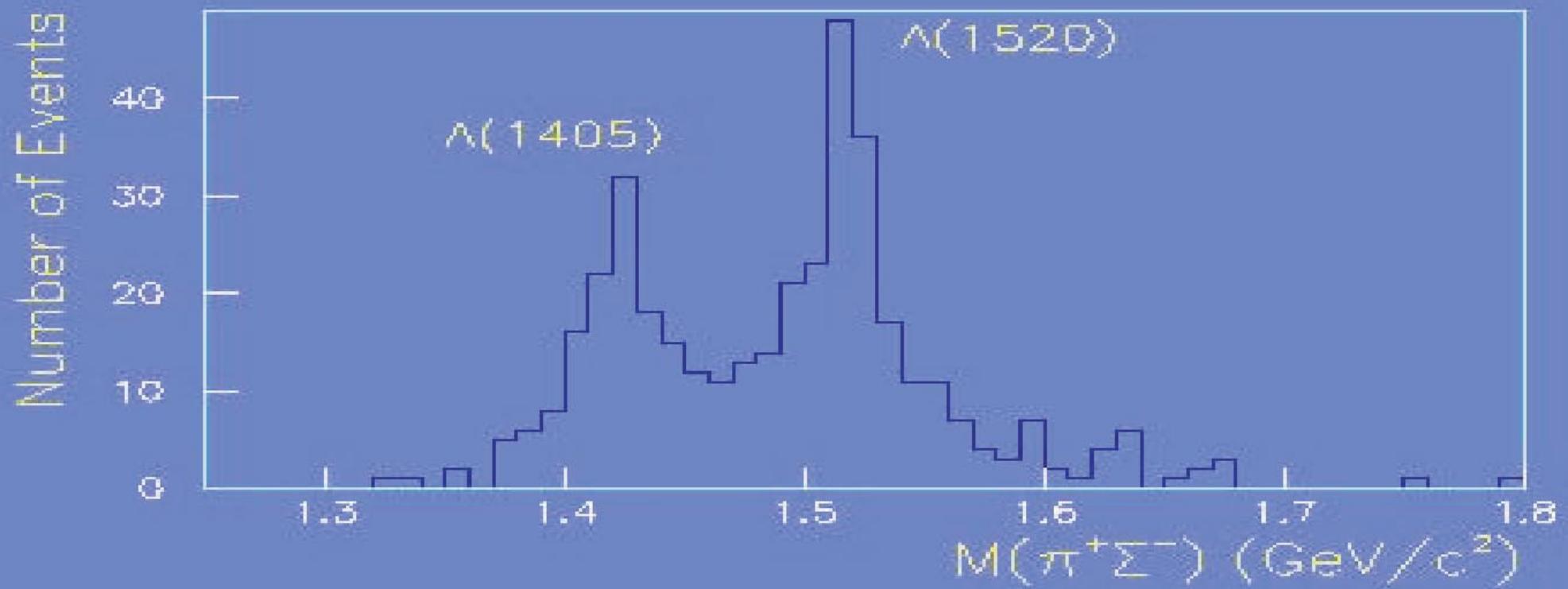


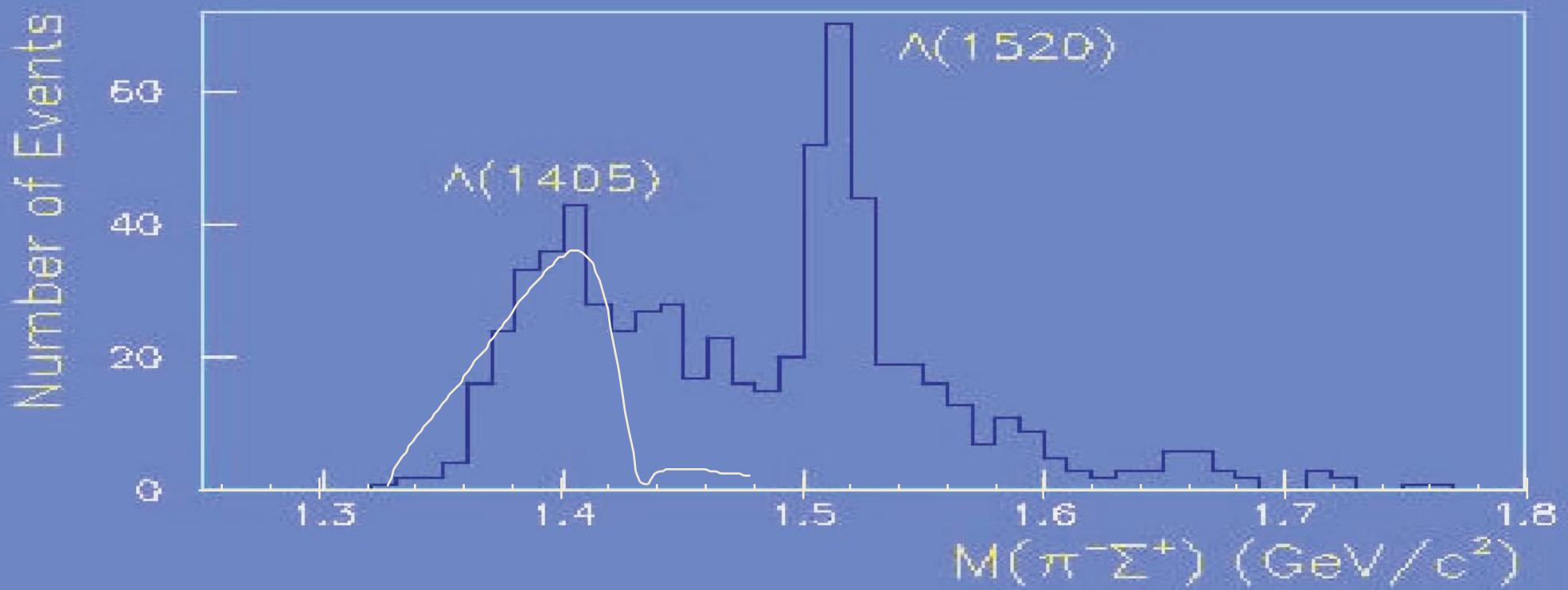
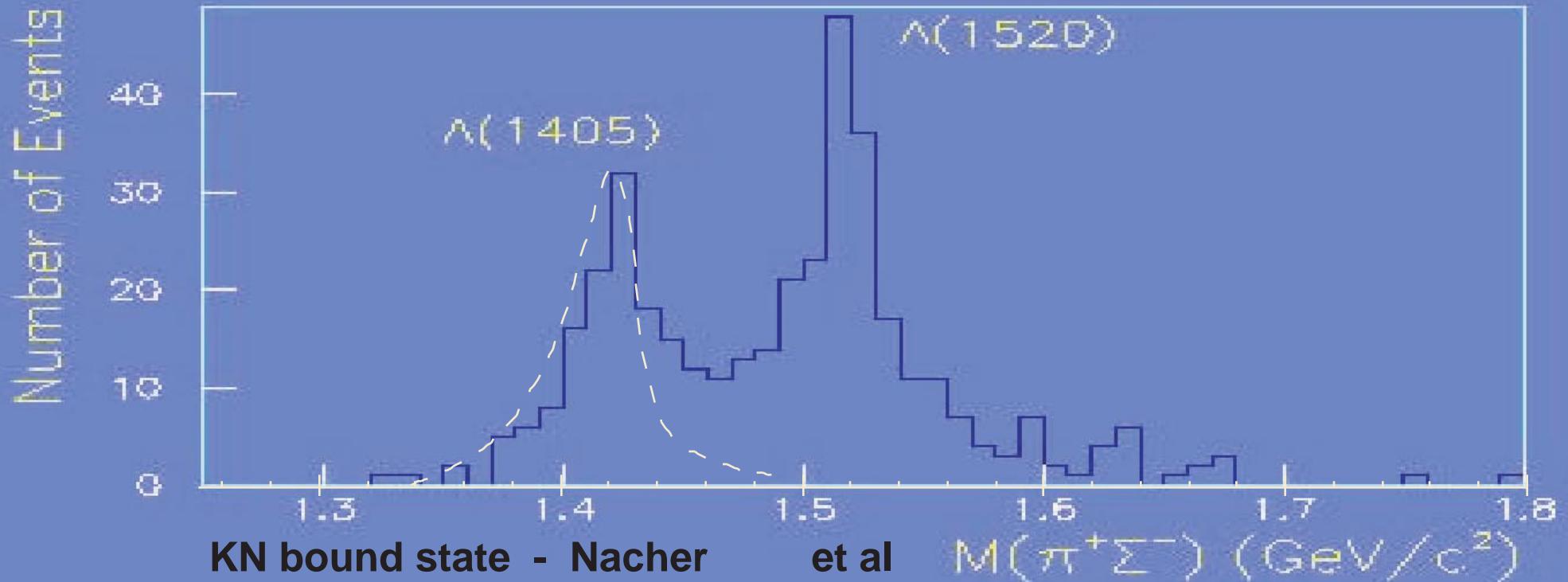
Preliminary Analysis for



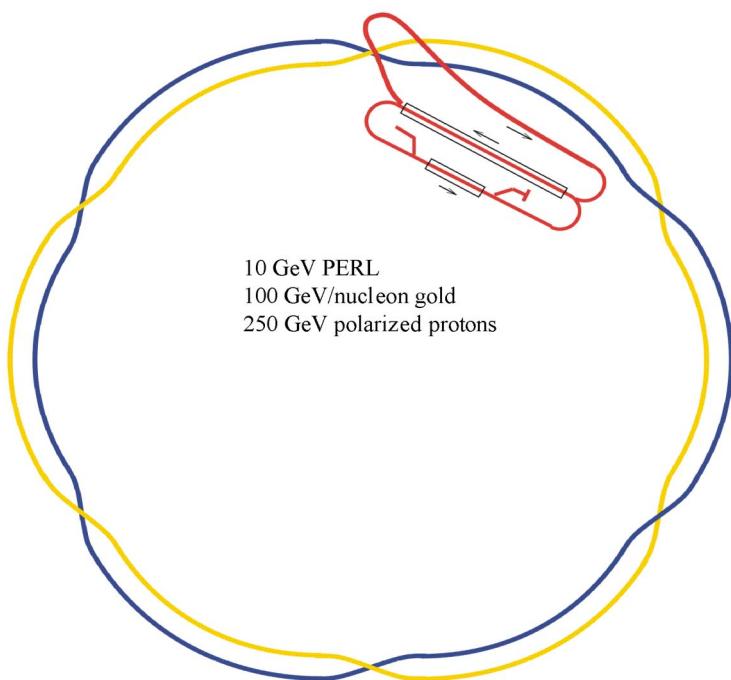
Missing-mass for $p(\gamma, K^+\pi)X$







eRHIC – a Polarized Electron on Ion or Polarized Proton in RHIC



current favorite design

- 10 GeV recirculation e^- ring
- 200 mA \Rightarrow high backscatter γ flux
- 28 MHz \Rightarrow 30 ns bunch spacing
- *very low* emittance \Rightarrow low ΔE_γ
- recirculate e^- for few 100 turns,
then dump to refill
 \Rightarrow no impact from backscatter γ
- interest in FEL
 \Rightarrow potentially *HUGE* γ flux

Backscattering from a 10 GeV eRHIC ring ?

	FEL	4ω Nd-YLF ring laser	Ar-Ion laser	
$\lambda(\text{nm})$	100	263	351	488
E_γ (max)	6.6 <i>GeV</i>	4.2 <i>GeV</i>	3.5 <i>GeV</i>	2.8 <i>GeV</i>

